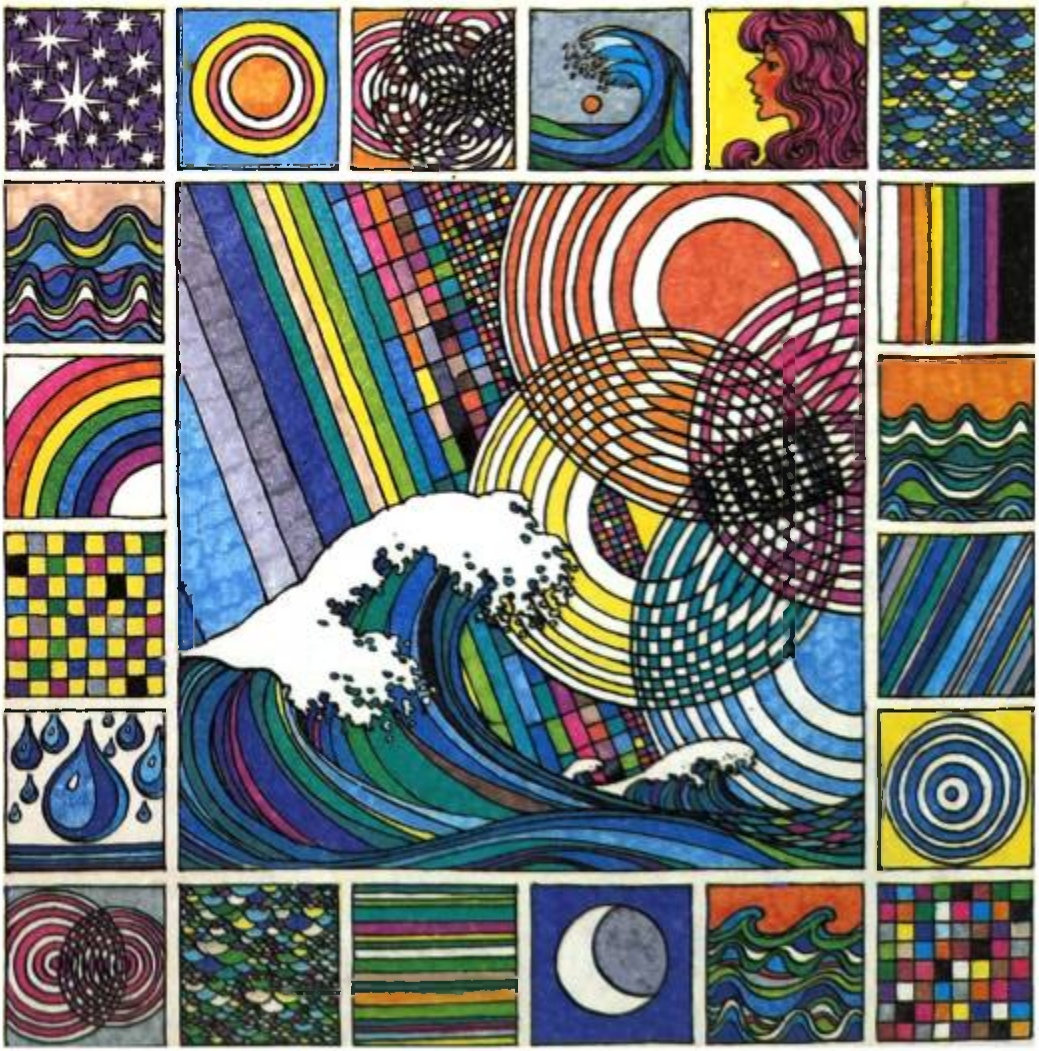
Andrei Rakin

DISCOVERY

WAVES BIG AND SMALL



Raduga Publishers has launched a new *DISCOVERY* series of general-knowledge books for young school-aged children. The *DISCOVERY* series provides children with a wealth of information on the world around them, as well as answering many of their questions. What, for instance, makes a train go along? What lives in the depths of rivers and seas? Is there life on the other planets?

This book tells the story of waves, be they waves in the ocean or ordinary radio waves. It turns out that every sound we hear is also a wave, though there are sounds that cannot be detected by the human ear... The author has a fascinating tale to tell about waves big and small.

Andrei Rakin

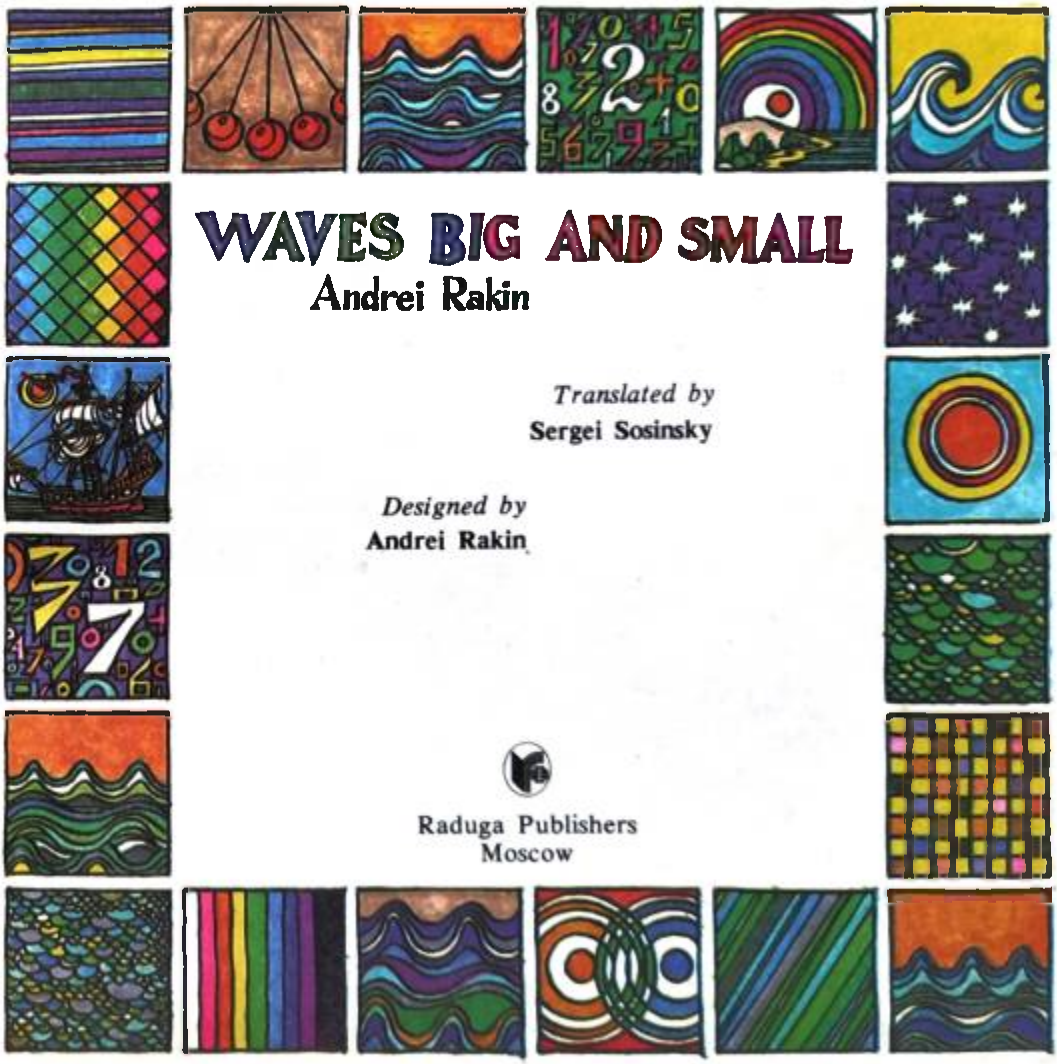
WAVES BIG AND SMALL

In Raduga's *DISCOVERY* series:
Chlenov A. *Geology in Pictures*
Dorokhov A. *You and Your Body*
Katin P. *Cells, Cells and More Cells*
Klushantsev P. *What the Telescope Tells Us*
Sakharnov S. *Who Lives in the Warm Sea?*

Raduga Publishers

1 p. 20 к.

ISBN 5-05-002487-0



WAVES BIG AND SMALL

Andrei Rakin

Translated by
Sergei Sosinsky

Designed by
Andrei Rakin

Raduga Publishers
Moscow

Translation from the Russian

А. Ракин

ВОЛНЫ БОЛЬШИЕ И МАЛЕНЬКИЕ

На английском языке

English translation
© Raduga Publishers 1990. Illustrated

Printed in the Union of Soviet Socialist Republics

ISBN 5-05-002487-0

Р $\frac{4803010201\text{-}670}{031(01)\text{-}90}$ 058-89

Contents

Seafarers

Introduction 4

Where Do the Waves in the Sea Come From? 8
The Adventures of a Raindrop 12
The Life of Swells 16
The Echoes of a Distant Storm 20
The Secret of the Ninth Wave 24
The Breath of the Ocean 27
The Big Wave 32
"Dead Water" 36
How Adults Play with Toy Ships 40

The Secrets of the Pendulum and the String

The Stubborn Pendulum 46
The Magic of Reason 50
The Holy Number 53
Underground Waves 58
Hunting the Invisible 60
Technology Without Science 64
The Ladder of Sounds 69
Putting Sound to Work 74
Traces of Mysterious Animals 78
Slowly But Surely 82

Bodiless Waves

The Story of Imaginary Ether 89
The Rainbow 93
"Rigid" Light 96
Heat Rays 98
Invisible Work 100
What Are Waves? 104

Conclusion 109

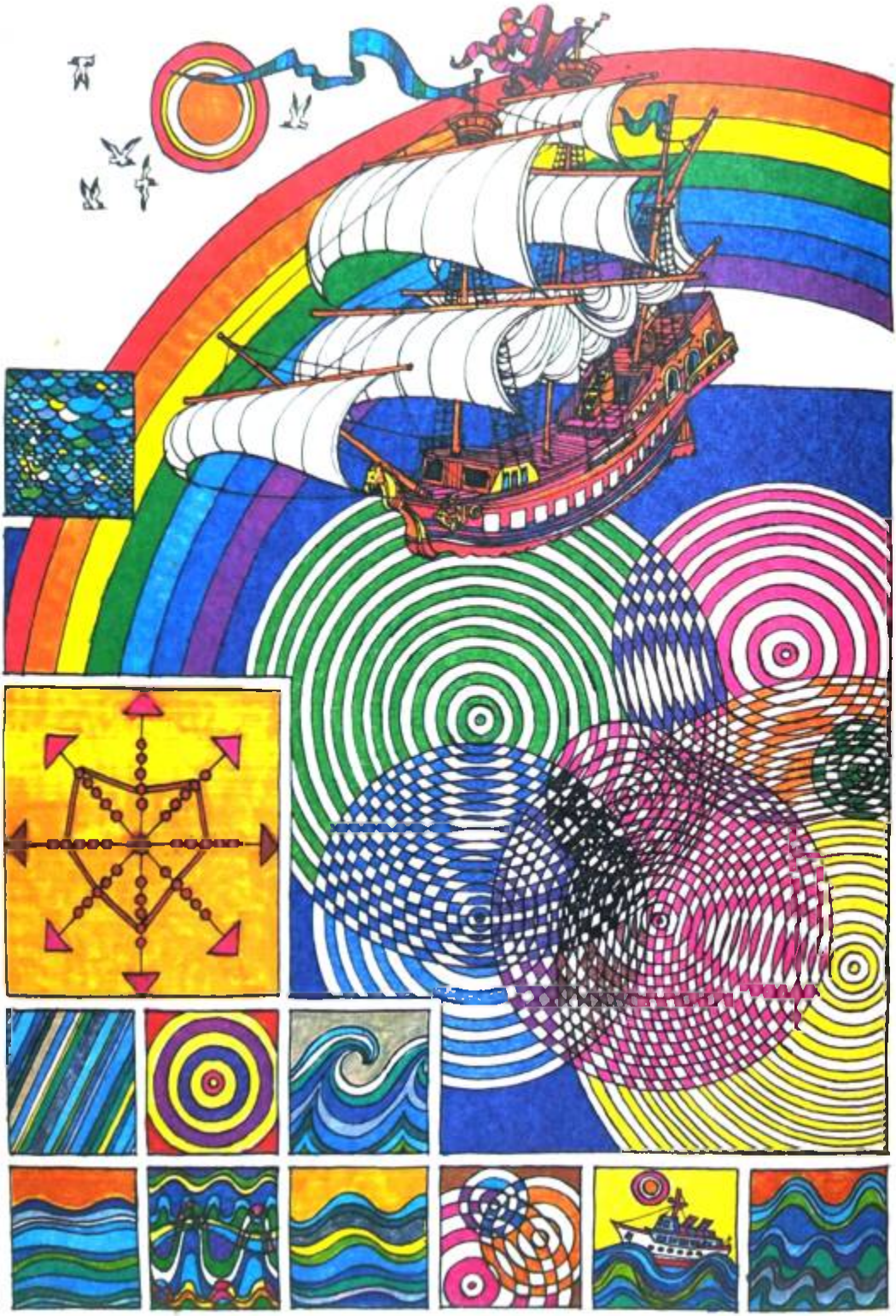
Introduction

Take a careful look at the world around you, and you may notice that it is filled with waves. Can you see them descending on us from the sky and quivering in the leaves? Can you hear them pulsating in each vein and engulfing you? Can you feel the ground trembling from them? If you can't, then this book will help you understand the changing world of waves. I will tell you about:

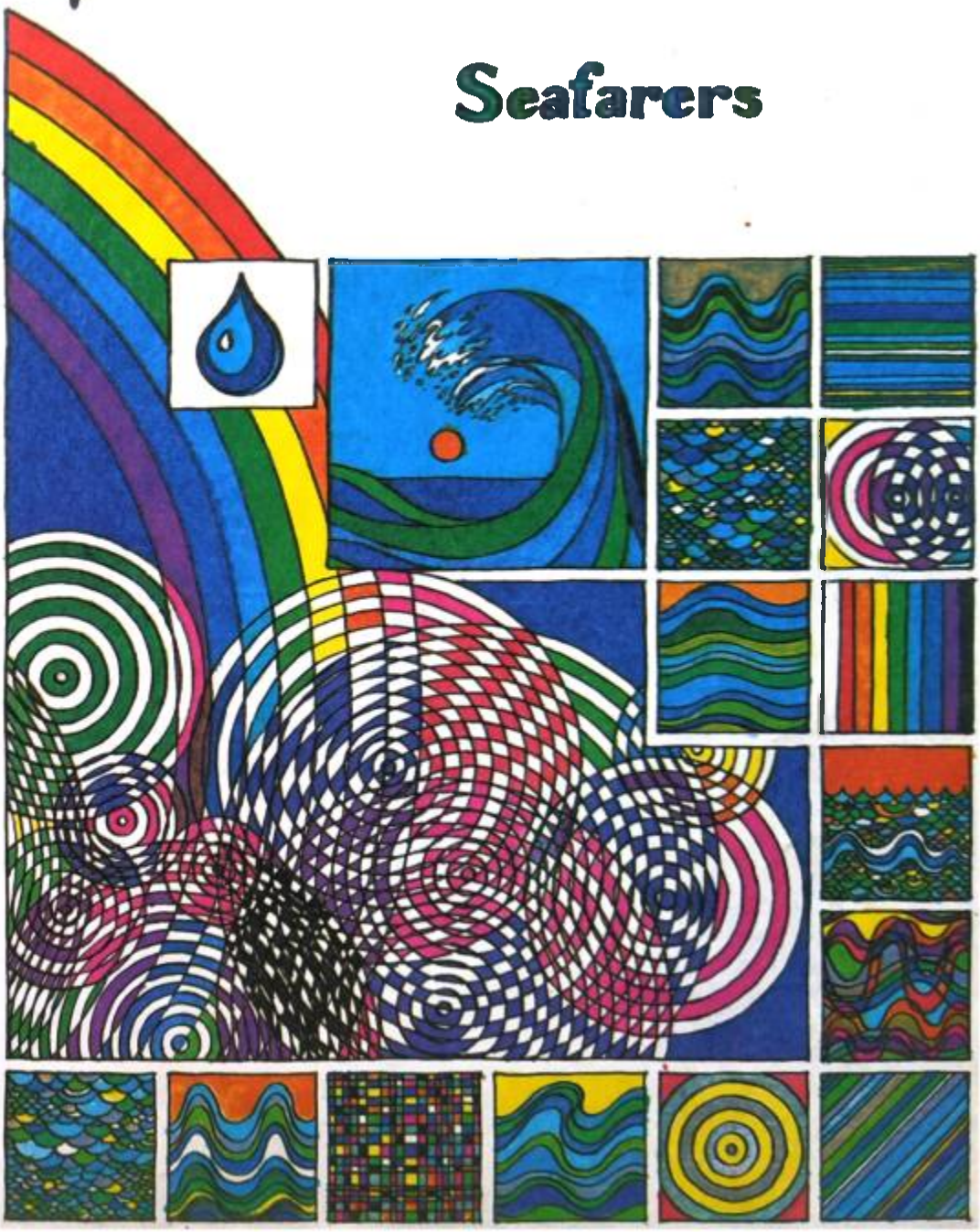
waves that can be seen but not heard,
waves that can be heard but not seen, and finally,
waves that cannot be seen or heard, but help people see and hear.

The world is full of waves, big and small, long and short. Some waves rise higher than the masts of the biggest ships, others you can't even see with a magnifying glass. There are waves that go round the world in the twinkling of an eye, and those that fit inside an atom. Some race through outer space at the speed of light, others are so slow you won't notice them even if you watched your whole life. Finally, there are strange waves that have no height (yet cannot do without length).

Our story begins with the most common waves, although they are not the simplest ones — the waves that are easiest to see. Those are the waves that we find on the seas and in a puddle of rainwater. The ones we are used to calling waves.



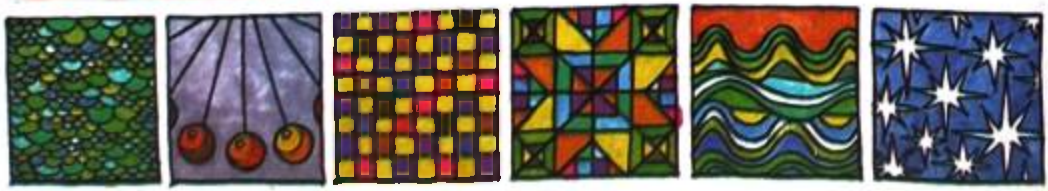
Seafarers



Where Do the Waves in the Sea Come From?

You can't imagine what deep scientific knowledge you possess about sea waves. More than a hundred years ago a rather witty fellow, Kozma Prutkov, offered an interesting thought: "When throwing pebbles into the water, observe the circles they form; otherwise throwing pebbles

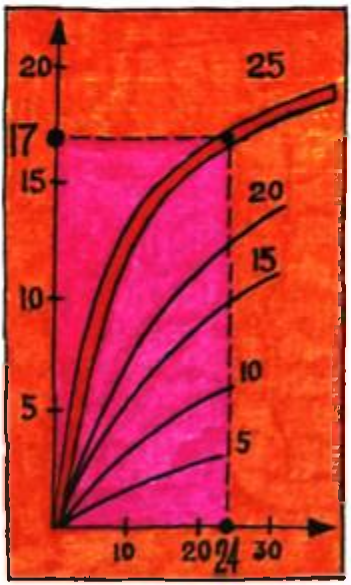
Ancient wind gods were drawn on maps in the 16th century only as an ornament or to explain the wind rose (see picture on left). But the romantic wind rose, in both science and practice, is actually a very serious thing. Just by looking at it the sailor knows almost for sure the winds that he will encounter, say, in October on the Baltic. And knowing the force and direction of the wind, an experienced sailor can predict the waves tomorrow and the day after



is nothing more than an empty pastime." All of us have thrown pebbles into the water, staged tempests in teapots, storms in plates and veritable hurricanes in the bathroom. If you take the time to watch how water behaves, if you ask enough questions and try to answer them yourself, it is indeed not an empty pastime but real research work.

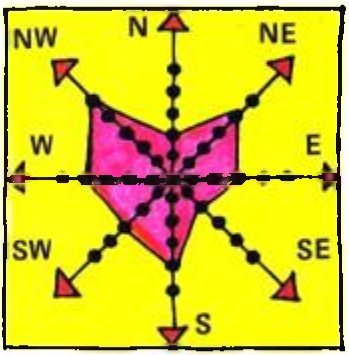
Each of us can probably answer the first question: where do waves on the seas come from? Waves are created by the wind. People realised this a long time ago. No wonder on old maritime maps the winds are

shown in the corners as plump heads huffing and puffing — blowing at the sea as if it were a plate with hot soup. If your mother allows such an experiment at the dinner table, it may help you discover a law of physics: the more space there is, the stronger the wind and the longer it blows, the higher the waves. That is what the formulas in thick scientific books about the ocean indicate. There are also tables enabling us to calculate the time needed to raise two-metre-high waves in the ocean.



Today seafarers rely not on the ancient rose, but rather on special tables and graphs. To learn the height which waves may reach in a strong wind (say 25 metres a second) blowing for a whole day, draw a line upwards from the number of hours on the horizontal axis to the red curved line, then move left to the vertical axis and the answer is found — 17 metres?! Well, that is possible! But in small seas (the Black Sea, for example) there is not enough space to produce such large waves. In the ocean, on the other hand, there are a few places where the weather is never windless and waves travel for thousands of kilometres. One of these dangerous places are the Roaring Forties between forty and fifty degrees latitude from the shores of South America to Africa

Here is another question which is more difficult to answer: why and how do waves move? Anyone will immediately say that waves move outwards in circles. Of course that is true, but it's not the whole truth. And it is not quite clear to us why they move in this particular way. In order to clear things up let's do the well-known physical experiment again: throw a pebble into the water.

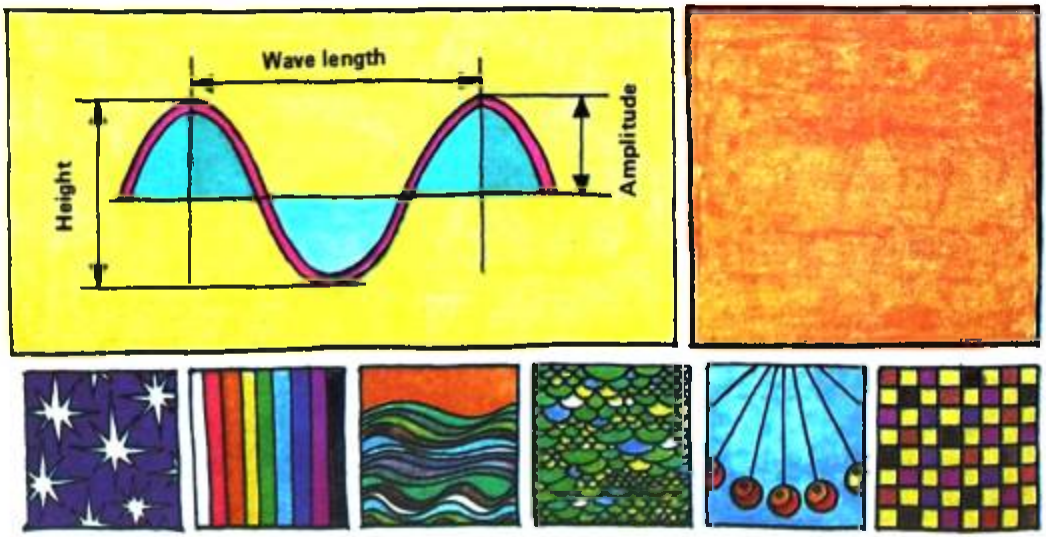


In order to understand what the wind rose is, it is best to draw one yourself. Mark the direction of the wind according to the weathercock every day. Then draw the cardinal points (like you have on a compass) and, for instance, if the wind blew from the northwest for five days, plot five centimetres from the centre in a northwestern direction. Do the same thing for all the other directions of the winds, join the dots and the rose is ready. The wind rose proves to be useful, however, only if measurements are taken thousands of times, as it takes many decades to study the winds in a certain place

The Adventures of a Raindrop

The pebble drops into the water. However, it is best to look at it as if from inside, so imagine that you are a raindrop falling into a pond. The water seems soft and yielding only from outside. Actually it consists of millions of drops pressed against each other. In order to gain space, it is necessary to push them aside rather unceremoniously. It is not so difficult to push away those nearest, but the ones further away are in no hurry to move. In the ensuing crush and disarray there is nothing the drops surrounding you can do but to somersault up where no one

The drawing shows the main properties of any wave. The wave length or period is the distance from crest to crest or trough to trough. As we can see the height is the difference between the level of the troughs and the level of the crests. The amplitude of a wave is often referred to as the difference between the average level (the position of calm water without any waves running over it) and the level of crests or troughs. The amplitude is usually equal to half the height of the wave

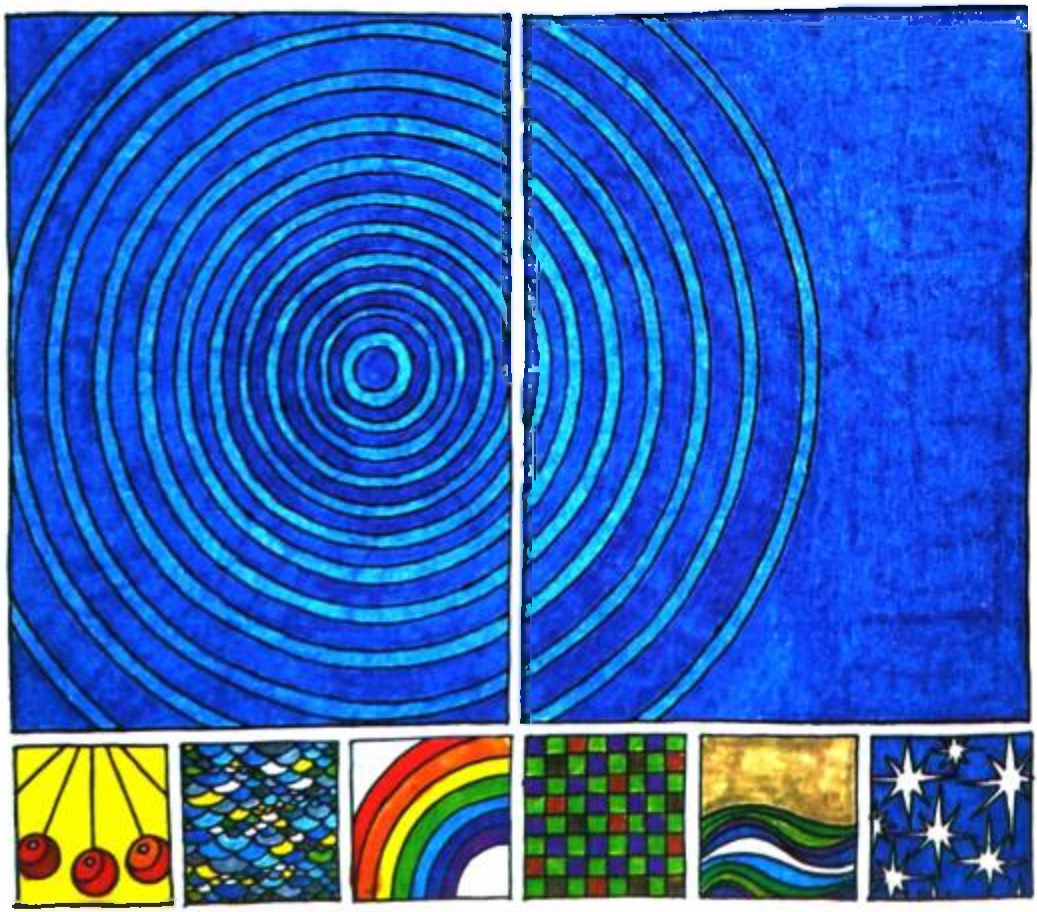


will crush them. That is how the first circle appears around the place where something has fallen into the water.

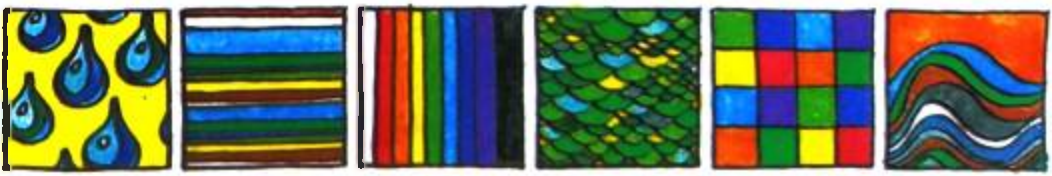
However, these drops are unable to remain above the water for long: their own weight forces them down, pushing up other drops further away. The circle becomes wider and wider, until the small wave (that's what it is) reaches the bank, bringing the news that the pond has one drop more.

By observing the life of a drop of water, you can learn a lot of remarkable things about the wave. First of all, each bit of water, having rocked with the wave, remains in the same place where the wave found

it. The wave doesn't take even one drop of water along with it. Only the outline, or the shape of the wave travels, while new drops of water are being forced up all the time. One moment they dance under the fast-moving crest, the next moment they have forgotten their restless visitor; meanwhile, the wave is stirring up their neighbours, only to leave them an instant later. The wave is only a bit of flying news, a report: "Something has happened somewhere." Recall the waves in a wheat field. Like the seafaring waves, they run over the whole field but not a single stalk travels with the wave. Each bows down to the wind but remains in one place firmly rooted to the ground, while the wave



runs on involving other stalks in the movement. Remember, this is the chief property of nearly all waves which distinguishes them from other phenomena of Nature. Second, waves running over the surface of the water are formed only by the drops which are on the surface (the wave forces only the upper layers of water to move). The water hardly responds to the splashing of the wave running over it at a depth greater than the length of the wave. (Look at the table: we call the distance between one crest and the next the length of the wave; it is useless to measure the distance along the crest: that distance may be big or small, but it will tell us next to nothing about the wave's behaviour.)



The Life of Swells

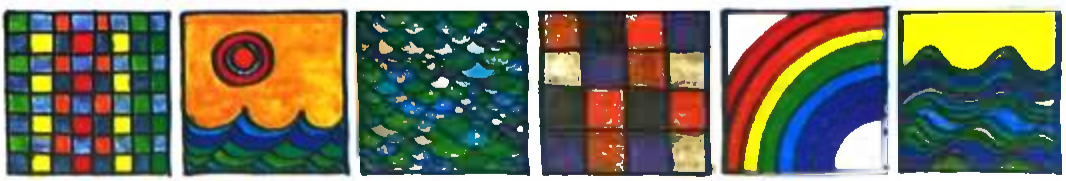
Ocean waves follow the same laws as waves in a pond or even in a plate of soup. All of these waves move in circles away from the place where they appear, only in the ocean they arise as a result of storm winds and the size of these waves is so great that a whole ship may disappear in the trough between two waves.

Let us look again at the table on page 10: if a fierce storm blows for several days in a row, the waves will reach heights of over ten metres. That's according to calculations, but eye-witnesses report waves thirty metres high. It may be assumed that in very strong hurricanes waves are even higher, but people who can tell us about them are difficult to find. The existence of such waves was confirmed recently by

means of satellites which looked from outer space into the centre of the most terrible typhoons. The optical devices revealed not only waves of tremendous height but another incredible phenomenon. In the centre of a major hurricane, where no ship can sail harmlessly, the just mentioned law concerning the wind and waves does not hold. A wind of enormous force drives a spray over a smooth surface of the troubled ocean, while the waves dare not lift their heads. They finally rise some distance from the centre of the hurricane.

The further the waves move away from the place where the storm plays havoc, the calmer they become. In windless, still weather the surface of the ocean rises and falls slowly — it is the only thing that tells us that hundreds of kilometres away a terrible storm is tossing ships from side to side. These sleepy waves or swells, as seamen call them, strangely combine slowness with continuous and relatively fast movement. Their height is almost completely overshadowed by their enormous length (the distance between crests may be more than a hundred

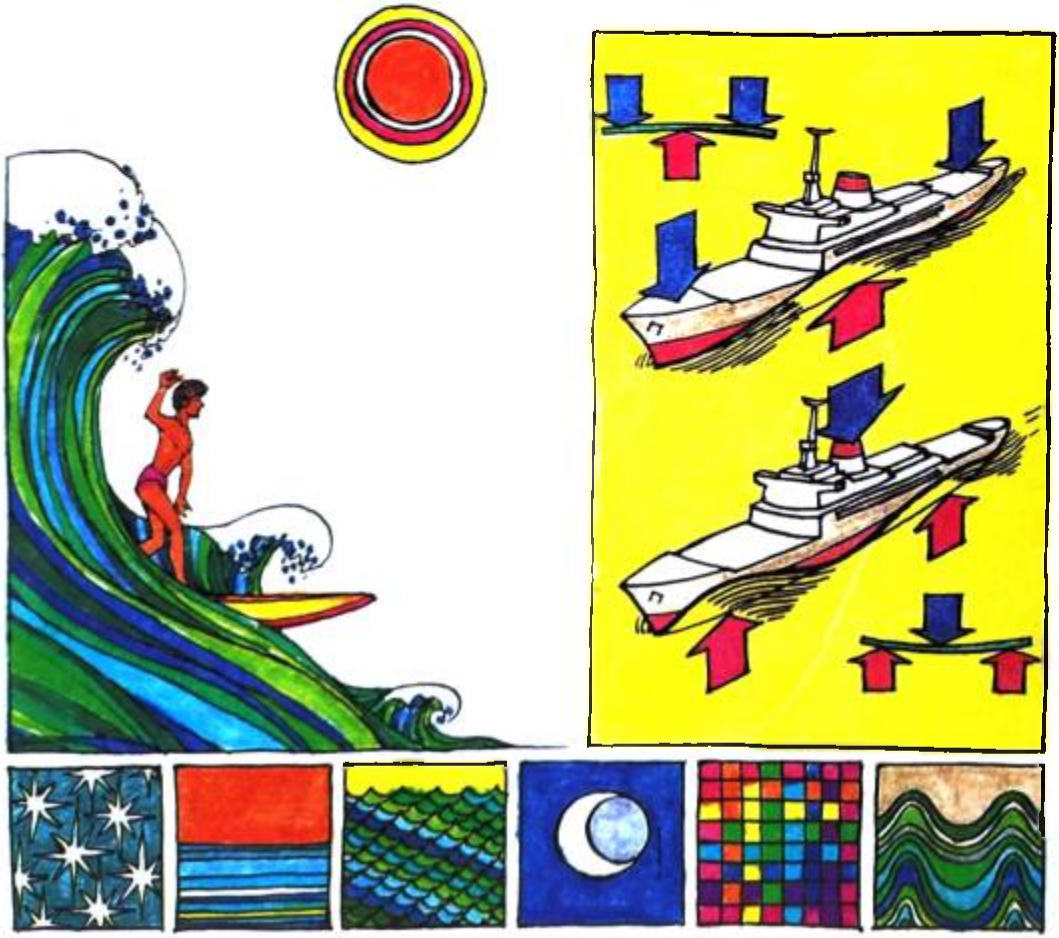
A ship sailing the high seas (see picture on left) is like a traveller trudging over hilly ground where long and gradual climbs alternate with sloping descents. Long waves with sloping sides (a) are not dangerous for a ship, but short ones (b), even if they are not very high, are a real danger. Swells of the latter kind often occur in the Caspian Sea



metres), so the usual steady breath of swells gently lifts or rocks the ships sailing over it. A person on deck doesn't notice that the wave which just rocked the ship has moved many hundreds of metres away in a matter of seconds, i. e. it could catch up with a passenger train.

The lazy run of swells has made possible an excellent sport known as surfing which somewhat resembles downhill skiing. The difference is that the "hill" of water runs after the person descending its slope sometimes carrying him for a distance of several kilometres along the shore.

An experienced captain doesn't fear the height of swells, the danger lies in their steepness. There are waves that are not very tall but short,



and if the distance between the crests is less than the length of the ship, the wave pushes the ship up in the middle leaving the stern and the bow in the air or will lay bare the middle of the hull. The ship no longer responds to the rudder, begins to keel, and sometimes breaks in half under its own weight, unable to withstand the repeated strain. When the captain hears the howling of the engine helplessly turning the propeller in the air, he realises that the real test of his seamanship has come. In order to break free of the gentle but relentless embrace of the swells one must know not only the behaviour of waves but also the specifics of one's own vessel.

The Echoes of a Distant Storm

A distant storm demonstrates its force again when the swells it has put in motion finally reach the shore. If the storm is thousands of kilometres from the nearest shore, the waves will cover that distance in a few days. By the end of the long journey (the storm would have subsided by this time), they are no more than a metre and a half high. But when the waves feel the bottom (and any wave — recall the second chapter — will feel the bottom as soon as the depth becomes less than the distance between the nearest crests), they begin to grow, their shape becomes sharper, the upper part bends over dangerously, and reaching

A wave running onto a sloping shore. In the open seas it was an ordinary surge, not too high, with gently falling sides. But where the wave runs along the sea bed, there is not enough room, and it rises higher and higher.

The lower part of the wave is slowed down by the bottom and the top part rushes ahead. Finally, the wave loses its balance and falls with a roar

the shore they break with a roar. The force of the impact is tremendous: imagine a freight-train with tanks of water crashing into a stone wall at full speed. The comparison is not accidental: the speed of swells is equal to that of a train, and each wave carries hundreds and thousands of tons of water.

The surf never subsides on an ocean coast: a day does not pass without a storm raging somewhere in the ocean, and the waves coming from it reach the furthest coasts. It is the surf which makes thousands of kilometres of the coastline a dangerous trap for sailors. From ancient times the waves crashing on the shore have caused people great troubles. Whole fortress walls made of granite, steel and concrete have been constructed in the sea to protect coastal buildings or moored ships from the fatal blows of the waves. Only recently was a breakwater invented which does not require reinforced concrete structures: a pipe with little

The road linking these numerous islands in the open sea runs along the top of a dike, an artificially-made strip of dry land. Such tremendous structures, which require the heroic efforts of many people, can be found at many ports on the ocean shore

holes is laid on the ocean floor and compressed air is pumped into it. The bubbles rise, creating an obstacle for waves no less serious than a stone wall. They suppress the movement of the wave, just like a layer of cotton muffles sound, disturbing the regular pushing of drops against each other.

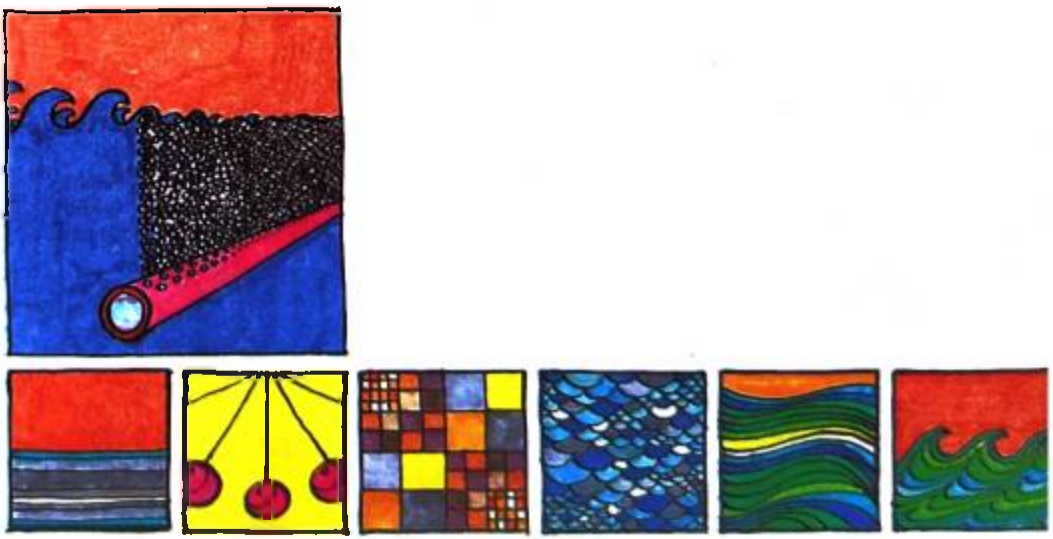
It is not enough to protect ourselves from the surf however.

People have now started to think about turning this long-time enemy into a friend or at least into a helper. In recent years engineers and inventors in different countries have devised several clever structures capable of harnessing the waves' destructive force for useful purposes.

We can clearly see an artificial shore-connected breakwater on the plan of the Moroccan port of Dar el Beida (formerly Casablanca, a name known to sailors of all times). The breakwater juts out from the rocky shore and safeguards the port structures from the ocean waves. From a bird's-eye view the breakwater seems to be a thin line with the surf foaming on one side all the time. But from close up the breakwater looks like a pile of concrete cubes or pyramids. Have the ocean waves scattered these blocks during a storm? Not at all, the apparent carelessness of the workers is actually quite deliberate: when a wave falls on these blocks part of the water runs into the numerous holes making the blow against the breakwater weaker. An obstacle with holes turns out to be more reliable than a solid wall consisting of the same concrete blocks

They have proposed stationing buoys in the surf zone — as they rise and fall with the waves they will drive electric generators installed above the surface of the water. Others intend to build embankments made of flexible shields — as they bend under the blows of the surf they will transform its energy into electric current.

Unfortunately, all these devices are still too big and expensive, and a practical way of making the waves breaking against the shore day and night work for man's benefit has not yet been found. Perhaps one of the young readers of this book will invent a new device. Don't be afraid: intelligence and a sharp eye may be worth more than volumes of technical literature.

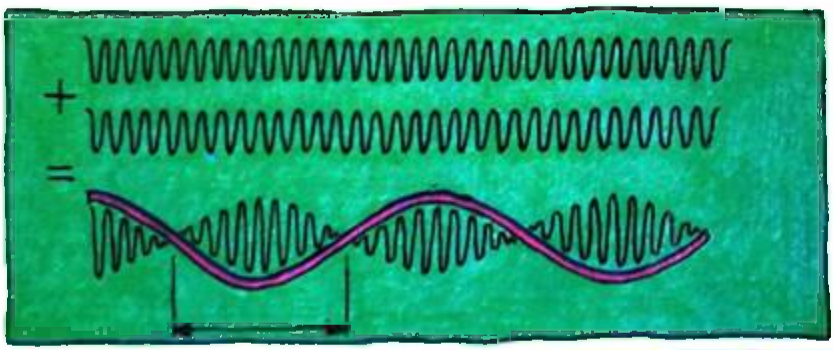


The Secret of the Ninth Wave

Waves come to the coast from a distant storm in a chain, as if in single file. Scientists call the sequence of waves a wave train. But a person who has seen the surf will object: "There is no sequence if the waves engage in a real free-for-all at the shore." One can hardly distinguish any pattern in the turbulent waves. The outstanding British scientist Lord Rayleigh who studied the laws of wave motion and was accorded the highest honours for his achievements once complained that the only

Waves running over a calm ocean from a faraway storm have a very regular shape: all the crests are of the same height (the waves have a constant amplitude) and they alternate evenly (the wave length does not change). It is curious that the ruffled storm waves assume a rounded, comparatively regular shape on their own once they come out onto a windless stretch of sea. Now some other waves approach. They are also regular in shape and have crests of the same height, only the distance between them (the wave length) is slightly larger than in the earlier waves. Let's attempt to put these waves together as happens when they meet in the ocean. Here's what we do: in the places where one crest is above another we make the top twice as high; where the trough coincides with another trough, the trough is twice as deep; but where the crest of one wave coincides with the trough of another or a trough falls on a crest they are mutually destroyed. The emerging picture is quite intricate, with large and small waves running in a certain sequence. The height of the waves seems to pulsate: the waves first grow then are reduced to nothing, occurring at regular intervals of time.

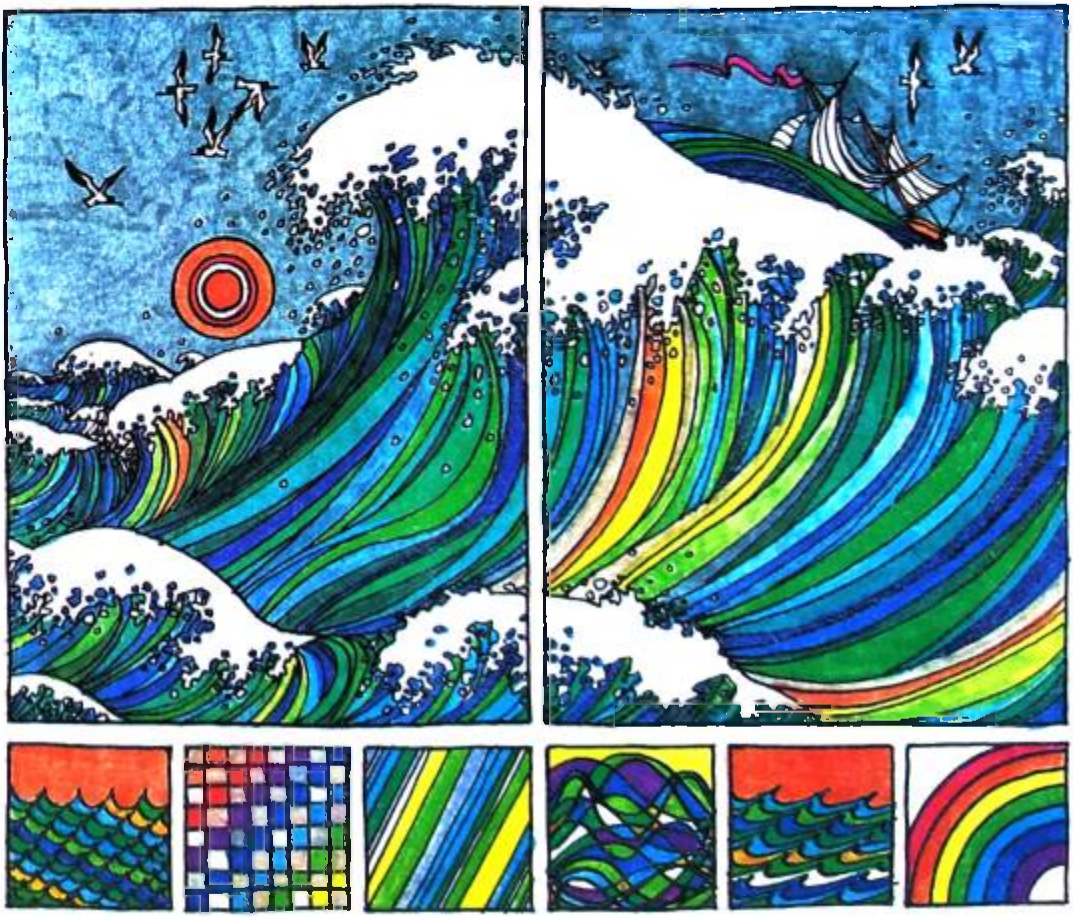
If not two, but six ordinary waves are put together, the disarray becomes even greater, but the disarray is only apparent. Actually the picture is repeated at similar periods of time. The largest wave is also repeated. While putting together different waves we see that the giant wave may occur anywhere, depending on the number of waves coming together and the mutual position of their crests and troughs



law sea turbulence conformed to was the absence of any law.

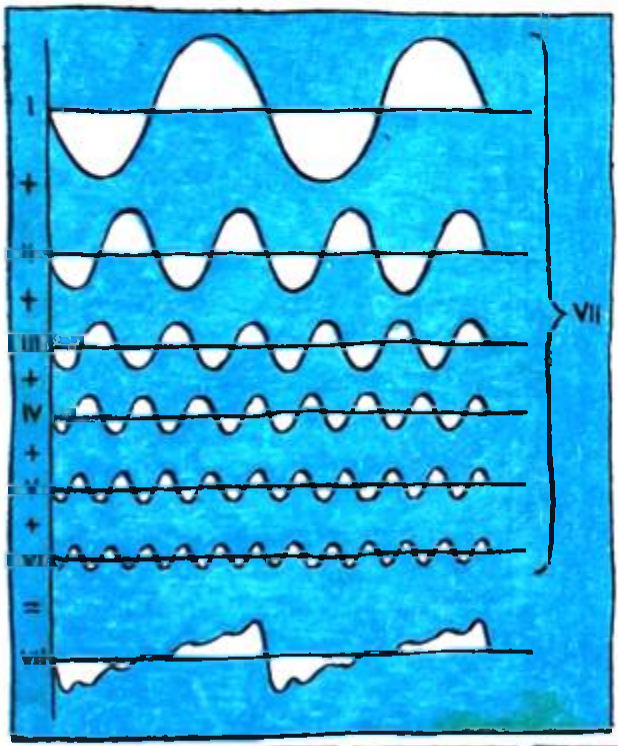
Yet Lord Rayleigh was too hasty in his conclusion.

It is difficult to discover a pattern in this chaos, yet we not only can, but should understand how the disarray emerges, how it is arranged. Waves come to the shore continuously from all directions: there are always dozens of storms raging on the enormous expanse of the ocean. Wave trains with waves of different heights and lengths move out from these places. They mingle together on the coast, and in the ensuing turbulence it is no longer possible to tell which wave comes from where. But there does exist a special law governing how wave trains combine. If the approaching waves don't change their shape for some time, the picture emerging as a result of the waves' combining (or the imposing of wave trains) will be repeated again and again. But sometimes we have to wait for a few minutes for a series of very different waves to



pass before the familiar sequence finally appears. Yet in several minutes about twenty waves will break against the shore! So we need patience to discover order in the seeming disorder. All of a sudden you notice that again a big wave is followed by a small one, then a middle-sized one, then a very small one, then more and more, until another big wave rolls in and the pattern is repeated all over again.

Sailors had the opportunity to observe dancing waves for long periods of time. Back in ancient times, when people were not sure about the laws of wave movement, a legend about a certain terrible wave appeared — either the ninth or the twelfth. When you go to the seashore, check that legend yourself — it contains a grain of truth. One of the series of waves will be larger than the rest. The question is which wave will turn out to be the largest — the ninth, the twelfth or perhaps some other?



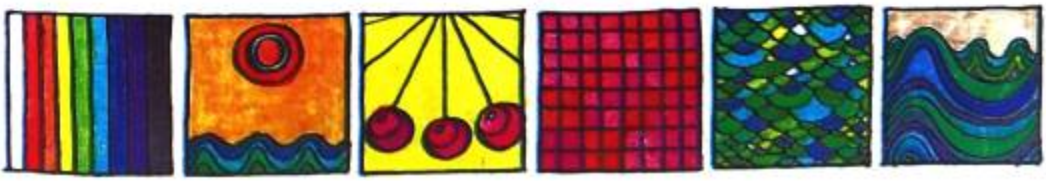
It is possible to notice another characteristic property of the interaction between virtually all the waves described in this book by looking closely at the series of waves running across the surface of a pond. There is total disorder in the places where the chains of waves meet, but when they come apart each of the chain goes on as if nothing had happened

The Breath of the Ocean

Among the waves rolling on shore all day long there are those you won't confuse with any other — the tides. But it would seem that waves are one thing and tides quite another. Why are they both considered waves? Let us look at the Earth from outer space or at least spin a globe. We will see that all the oceans of our planet are connected to each other in many places and that it would be more correct to refer to one World Ocean — a boundless blue expanse on which the continents are distributed like islands, taking up only a third of the Earth's surface.

It is in the World Ocean that the tide wave has gained momentum — it encounters almost no obstacles on its eternal circular run. There are only two periods of tides: when one crest runs along the Pacific Ocean its only brother rolls over the Atlantic. The height of that wave is enormous, sometimes reaching twenty metres, yet its length is so tremendous that even twenty metres seem quite modest. Its steepness (about a metre per thousand kilometres) can be detected only by the most sensitive instruments installed on satellites.

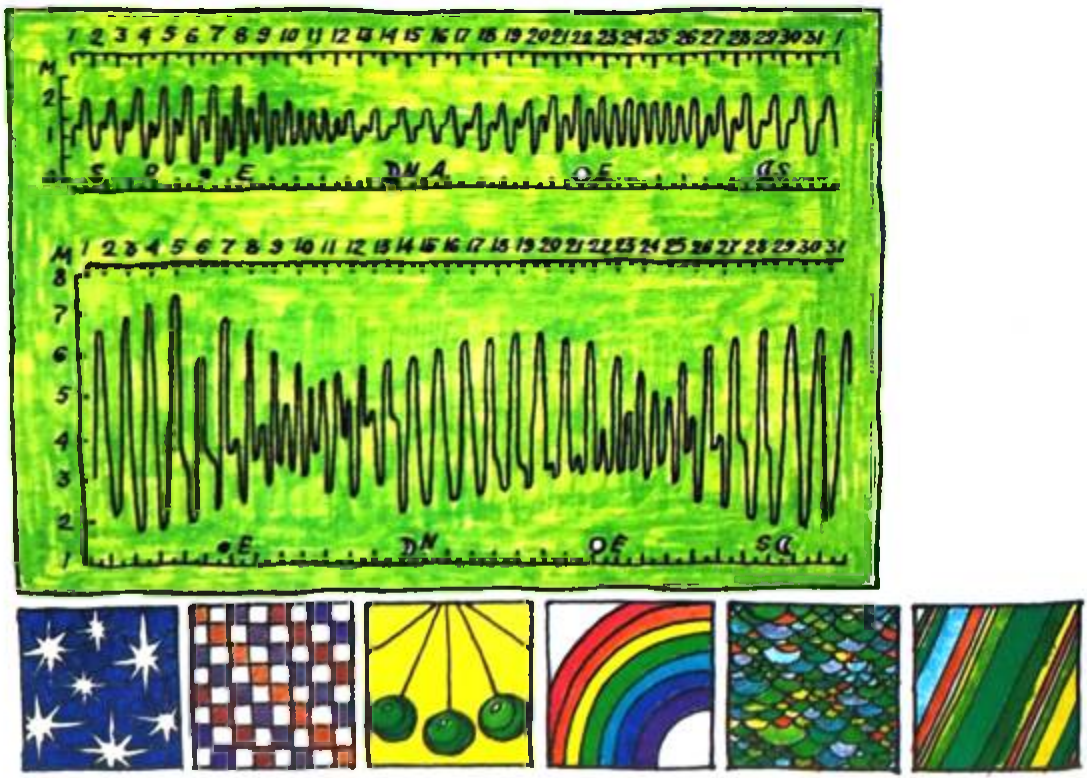
That wave visits all the shores of the World Ocean twice a day. In places it is almost unnoticeable behind the usual splash of the surf, but in other places it reaches the height of a five-storey building. People have grown accustomed to the fact that day in and day out, as inevitably as the Sun rises and sets, the tide floods the shore gradually and just



as slowly recedes. The inhabitants of coastal areas go about their work according to the schedule of the tides.

In the mouth of the Amazon River, the Yangtze and some other large rivers flowing into the open seas, the tide wave produces bores — tall waves reaching several metres that roll up the river for dozens of kilometres. These waves would have caused great damage if people

The graph shows how the water level changed in one place of the ocean shore. Doesn't it look like the sum of two waves we just plotted? Two tide waves do come together here: the stronger one is due to the pull of the Moon, while a relatively smaller one is produced by the Sun's gravity

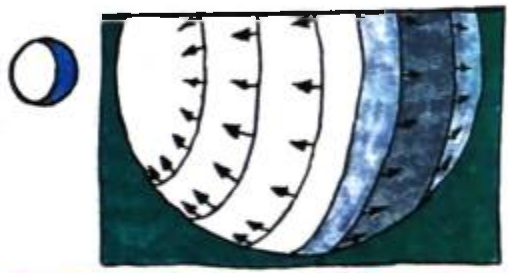


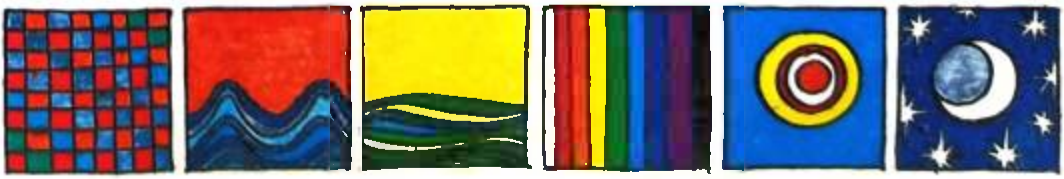
had not learned to cope with them. The river captains even allow themselves a daring escapade: not long before these waves come into the river's mouth several boats line up across the channel and when the waves enter the river with a roar the captains skilfully catch the first wave, and much like surfers speed to a place which they would otherwise have reached only after several days of struggle against the river current.

People are not the only ones who have adapted to the steady breath of the ocean. There is a whole community of creatures whose life conforms to the rhythm of the tide waves: half of the time they bask in the sun

The influence of the Moon on the water mass of the World Ocean may be imagined (on a very distorted scale of course) as shown in the picture

The figures indicate the hours of the highest tide in the English Channel

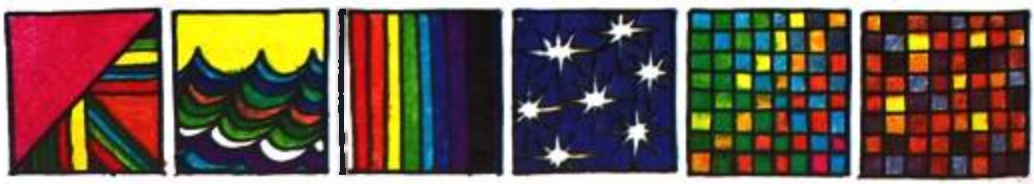




and breathe air, and the other half they live comfortably underwater. Hundreds of millions of years ago it was the tide that helped ocean creatures adapt to the air on dry land, and subsequently, in the course of evolution, gave rise to the variety of life on land.

The tide wave, however, arises not as a result of a storm (what storm could produce a wave half the Earth long?). It is due to the influence of the Moon. There is every reason for you to be surprised — even Galileo Galilei, a great astronomer of the 15th century, refused to believe the incredible link between tides and distant celestial bodies.

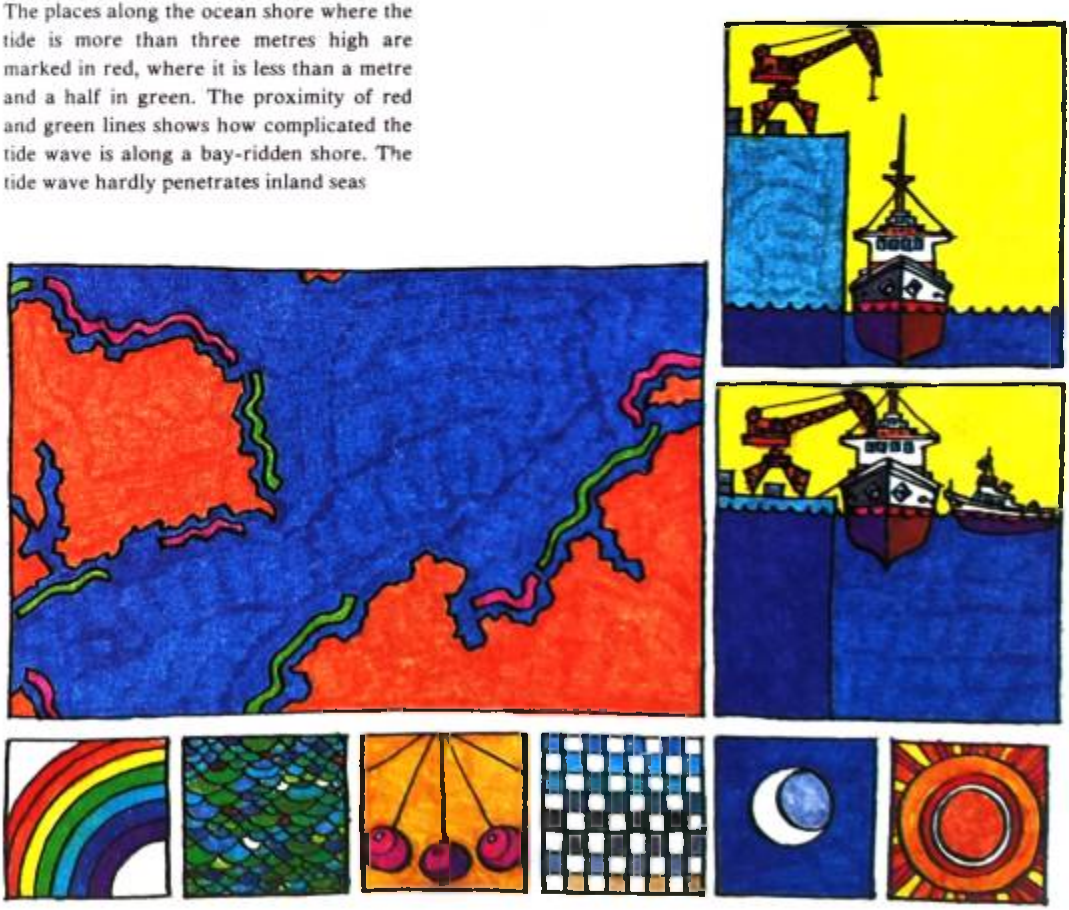
It is easy to understand Galileo. In his day astrologists, star-gazers and fortune tellers explained anything by the position of the stars or the influence of the planets. Even then educated people had no respect for such conclusions, and Galilei himself was so irritated by these ideas that he lapsed into the opposite bias, rejecting any link between celestial and earthly phenomena (these things happen even to great thinkers). The influence of the Moon on the Earth's oceans, however, is very complicated, and it is not possible to explain the finer points in this book. Briefly, the Moon, by its gravitational pull (though not very strong) slightly changes the Earth's rotation, and the resulting forces pull the water envelope of the Earth towards the Moon and in the opposite direction. These two water bubbles run after the Moon. But these "bubbles" or the tide waves do not keep up with the Moon, constantly lagging behind. (Do not forget that the Moon goes round the Earth in 28 days, and not as fast as it seems to us. It is the Earth itself which revolves rapidly around its axis making one rotation a day. But for the tide wave only the position of the Moon in respect to the Earth is important.)



Second, the Moon's tide wave is compounded by another tide wave produced by the Sun (by what seems to be its rotation around the Earth). And if we keep in mind that the shore damps the wave in some cases, and intensifies it in others, it is clear why it is impossible to calculate tides for many centuries to come.

It is easy to imagine the troubles sailors and port personnel would have were the quays built in places where the tides are very strong. When the water recedes, the quays tower over the moored vesseles, when the water rises, the quays nearly disappear in the waves

The places along the ocean shore where the tide is more than three metres high are marked in red, where it is less than a metre and a half in green. The proximity of red and green lines shows how complicated the tide wave is along a bay-ridden shore. The tide wave hardly penetrates inland seas



The Big Wave

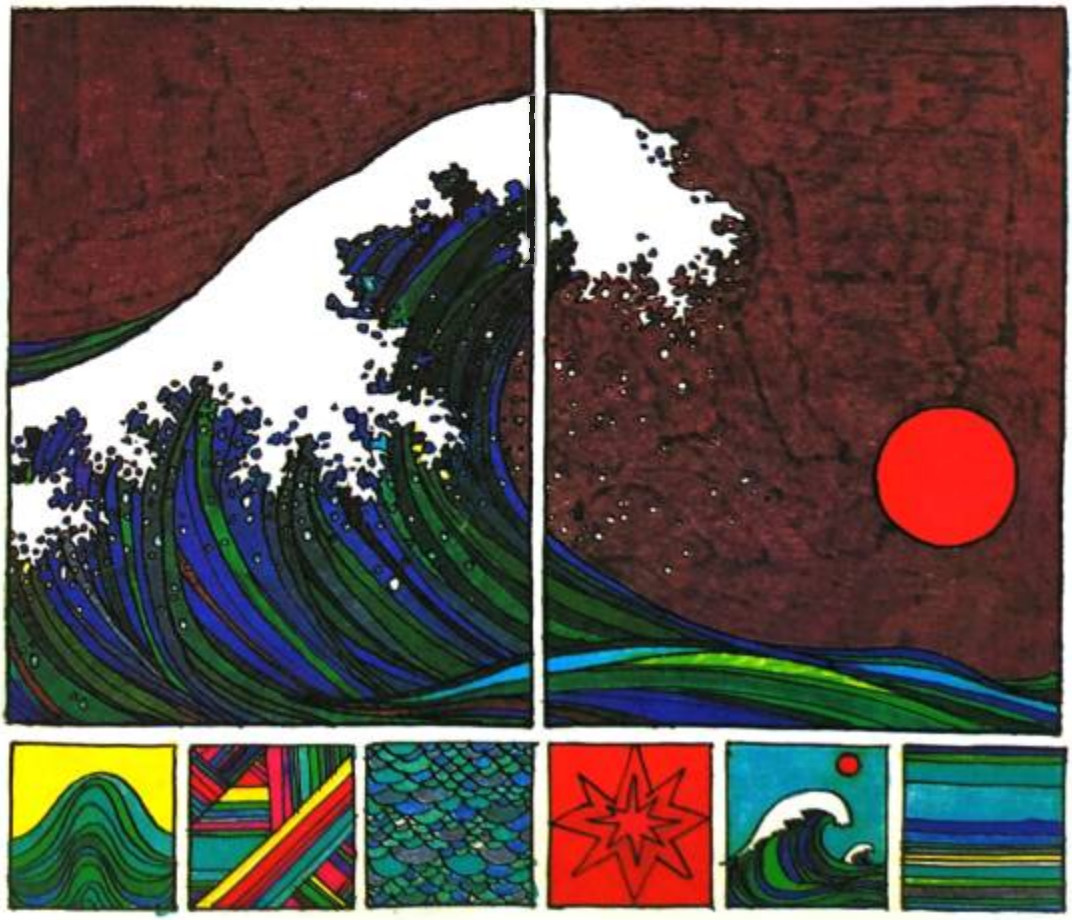
You would think that a wave larger than the tide wave is not to be found in the ocean. Indeed, a longer wave would simply not fit, but there are waves higher than the tide wave. The Japanese, who have suffered most from it, have called the highest and most terrible wave of all tsunami which means high water or big wave. The usual, even very big waves arising during a storm set out on their journey across the ocean in long chains. But the tsunami or tidal wave, as we call it, is a lone wave (although there may be five or ten of them in a row), and is produced not by a storm but by some natural disaster such as an underwater earthquake or the eruption of an underwater volcano. In this sense the tsunami is more like a wave produced by a stone thrown into the water. But such a wave could be caused by an enormous rock the size of a mountain.

津浪

These characters meaning the Big Wave were terrifying for Japanese from time immemorial

Few people have seen how a tsunami arises, but a few kilometres from the site the wave becomes even less noticeable than the swell from a distant storm. The tsunami moves at an incredible speed — more than seven hundred kilometres an hour — yet the long, sloping sides conceal its speed and height so well that occasionally sailors on ships along its route have failed to notice it. But as soon as it reaches the shore, people suffer from what is probably the worst catastrophe the ocean has in store for them.

Usually, an unexpected low tide begins shortly before the killer wave arrives. The water recedes many hundreds of metres from the shore. This is a sure sign that calamity is imminent: in a few minutes an enormous



wall of water will descend upon cities and fishing communities, sweeping away everything in its path. The fantastic force of the wave can be judged by an event which occurred about a hundred years ago on the Pacific seaboard of America. A tsunami lifted a steamship anchored in the bay, carried it over an entire portal city and gently deposited it on the ground far inland. It is said that the crew, while awaiting the decision of the owner who lived on the other side of the Earth, did not abandon the ship and even planted vegetable gardens around it. Unfortunately, such happy endings are exceptionally rare.

How is it possible to protect people from this disaster? It would be good to know about the fatal wave at least an hour before it comes, so people could go inland and ships into the open sea. It is possible to forecast the arrival of tsunami by means of other waves which arise simultaneously with the terrible wave and run through the Earth's crust, though much faster than the tsunami. We will consider these waves — seismic waves — later in this book. Let us only mention now that scientists from Novosibirsk have learned how to determine the direction of the danger, while experts at the Applied Physics Institute in Gorky developed a method of calculating how a big tidal wave will behave once on shore. So it is possible to determine the places on the coast where the Big Wave is most dangerous.

The sites of the most frequent earthquakes and volcano eruptions are marked on the map (left) by dots. The string of dots surrounds the whole Pacific Ocean. Each time the ocean bed shakes in these parts the devastating wave brings calamities not only to the nearest shores but also to the opposite continent which it reaches in a matter of hours without meeting any obstacles along the way. Minor, not very dangerous tsunami occur on the Pacific Ocean every week, but the inhabitants of the coastline areas should be ready for the arrival of a really catastrophic wave. Many Japanese villages have similar stone obelisks with the same inscriptions: "When you feel an earthquake be ready for a tsunami, when you see a tsunami run up a mountain."

"Dead Water"

In April 1963 the world learned that the American atomic submarine *Thresher* had disappeared in the ocean with 129 men on board. At first it was difficult to believe: how could a huge missile-carrying submarine vanish without a trace? But a meticulous search failed to yield any results. The US Department of Defence began an investigation, believing that sabotage was involved. The disappearance of the *Thresher* would have remained another unsolved mystery were not oceanologists — scientists who study the ocean — engaged in the search. When it was learned where the submarine had been located when it transmitted its last message, they provided the answer. Waves were to blame for what had happened! But not the waves we have spoken of so far, not waves on the surface of the ocean but underwater waves. Scientists knew that silent storms raged under the calm surface of the sea and waves almost a hundred metres high slowly and noiselessly moved there.

In order to understand what we're talking about, I'd advise you to carry out an experiment. Carefully pour two liquids which don't mix well into a glass, the lighter one second so it'll be on top. The simplest thing

It would be better to do the experiment with water and oil in a larger vessel, but that would require too much oil

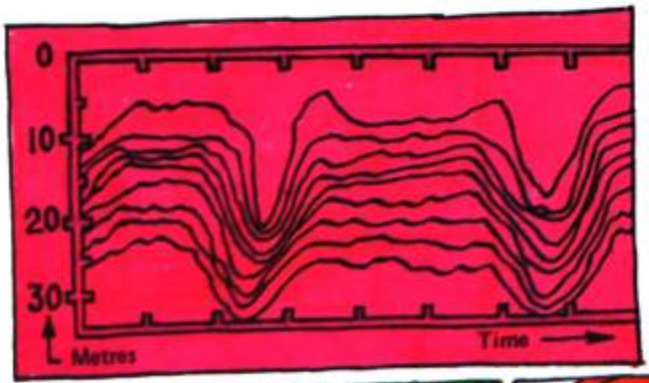
is to take water (with a bit of food colouring) and pour cooking oil on top. There will be a distinct boundary between the water and the oil.

Now rock the glass gently. Small waves will run across the oil on top, but we are only interested in what happens on the boundary between the oil and the water. If we rock the glass slowly the boundary begins to bend smoothly — waves also pass along it but slower and steeper than the ones on the surface. These are underwater waves: they exist deep inside the liquid, or, to be more precise, on the boundary between liquids of different densities.

There are also distinct boundaries between layers of water with different properties in the sea. The heavier water (water which is colder

or contains more salt) sinks to the bottom, while the lighter water rises. This phenomenon is particularly obvious near straits or in the mouths of rivers where masses of water with different properties meet. The *Thresher* was lost in the Atlantic Ocean directly opposite the Strait of Gibraltar through which an enormous stream of cold water flows into the Atlantic at a level much lower than the ocean surface. This hundred-kilometre-wide "underwater river" flows into the deep canyons of the ocean floor in several waterfalls. Oceanologists were aware that large underwater waves formed on the boundary between the layers. These deep-sea giants cannot be seen on the surface of the ocean — they are too slow to produce even slight ripples on the surface since the period of one wave is several hours. It seemed convenient for submarines to travel on the boundary between heavy and light water: they move with great stability, and are not tossed up and down. But if a silent, slow underwater storm begins along the boundary, the smooth road begins to rise in steep hills and fall into abrupt and deep depressions. If a captain

It is impossible to see an "inner storm" in the water depths. We can only observe its traces: for example, as the readings of temperature gauges (for the wave recorded on this band the period was only 10-15 minutes and the amplitude 5-6 metres)



has turned on automatic navigation controls and fails to notice that his instruments indicate a storm, the ship may slip down the slope of an underwater wave, plunging so deep that it will be crushed by the weight of the water lying above it.

The oceanologists proved to be correct: in the area they indicated, where there had seemed to be no threat, a special deep-sea expedition found the crushed remains of the submarine. Subsequently scientists have worked out special recommendations for submarines to avoid new catastrophes underwater.

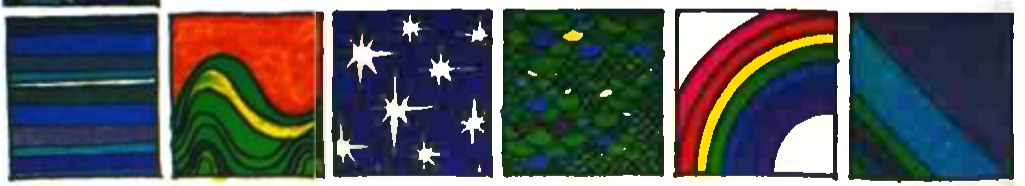
Underwater waves occasionally interfere with those sailing the surface of the sea. A long time ago sailors noticed that in the North Sea, for example, there are places where fast ships seem to mark time: although the engines strained, the ships moved like tortoises. This strange phenomenon was called "dead water", but no one could explain it. Only after the Second World War did scientists manage to prove that underwater waves were also to blame for the mystery of "dead water". When the boundary between layers of different water lies only a few metres below the surface, the ship's propeller only produces the underwater waves and disperses them in the boundary area, consuming almost all the engine's energy.

How Adults Play with Toy Ships

For ages the most experienced of sailors were unable to understand many of the ocean's mysteries, and most extraordinary legends appeared, even in the 20th century. Only scientists realised that the most varied wave miracles strictly conformed to laws of physics. The strength of science lies in rigorous experiments, direct questions and honest answers. In order to learn more about the nature of waves, they must be observed closely. To do this large tanks and pools have been built and, with the help of machines, the most varied kinds of waves are produced and measured from all sides, with all kinds of obstacles put in their way. Even little toy ships are sent over these waves to see how they behave.

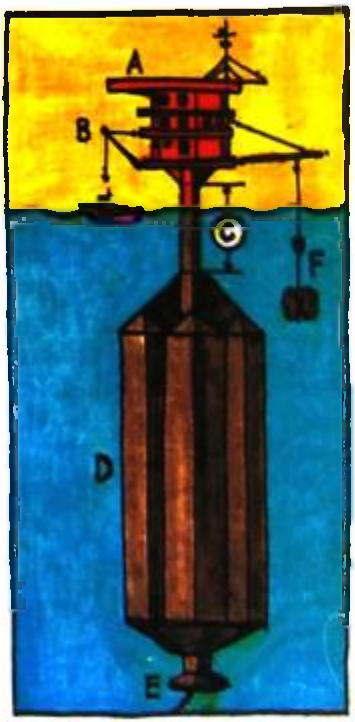
However, in an ordinary pool, like a swimming-pool, it is impossible to produce a large wave, the pool is too small. Really big waves (several metres high) are produced in an endless wave-canal. The latter is indeed endless, although it takes up relatively little space — it is simply curved in a circular shape. Gale-force winds which last for hours are produced in such canals with the help of fans, and the waves running non-stop around the circle can reach the size of real storm waves.

Although these experiments resemble children's games, their importance does not have to be explained: knowing how a little ship sails over a little wave, it is possible to predict what will happen to a big ship in a real storm. Without risking anyone's life, it is possible to stage a thousand



shipwrecks, and carefully consider how to avoid them. These adults' games are called scientific and technical models. But it is not possible to understand all the specific features of ocean waves by means of laboratory experiments. It is necessary to observe them in their natural surroundings as we do wild animals. But how can this be done? There is no point in observing them from shore: the waves there behave quite differently than those on the open seas. Perhaps from aboard a ship? It is also difficult. The ship itself is a toy to the waves — some waves simply cannot be seen from the deck, while others seem to reach the sky. What we need to do is build an island in the ocean small enough not to interfere with the waves but which would remain completely still.

This is what a floating island looks like; it is known as a stabilised manned sea buoy:
A. This is not just the roof but, as it would be on a ship, the upper deck. It may also serve as a helicopter landing site. On the right it has a real mast like any ship needs: it has signal lights and it also supports the radio aerial.
B. These are large and comfortable cabins and, of course, research laboratories.
C. The bottleneck of the buoy is not that thin: a lift goes through it taking people to the lower decks of this enormous structure.
D. The fuel, compressed air supplies and batteries are located at the very bottom.
E. The anchor cable is fastened to this bulky "earring". The anchor might be needed if it is necessary to make the island stay in one place. But from time to time, it is more useful for it to drift with the ocean currents.
F. The island has all kinds of instruments on the outside to observe the wind, current, waves, to listen to the voice of the ocean or receive signals from outer space

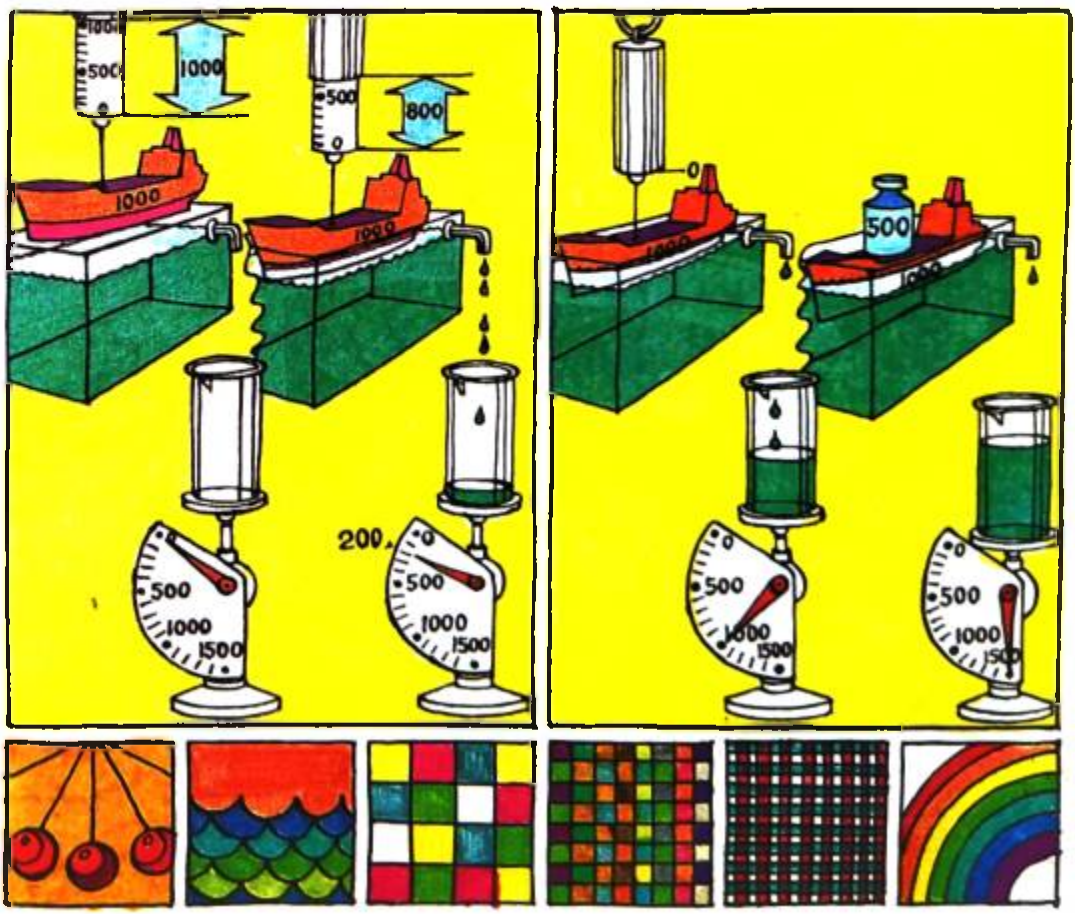


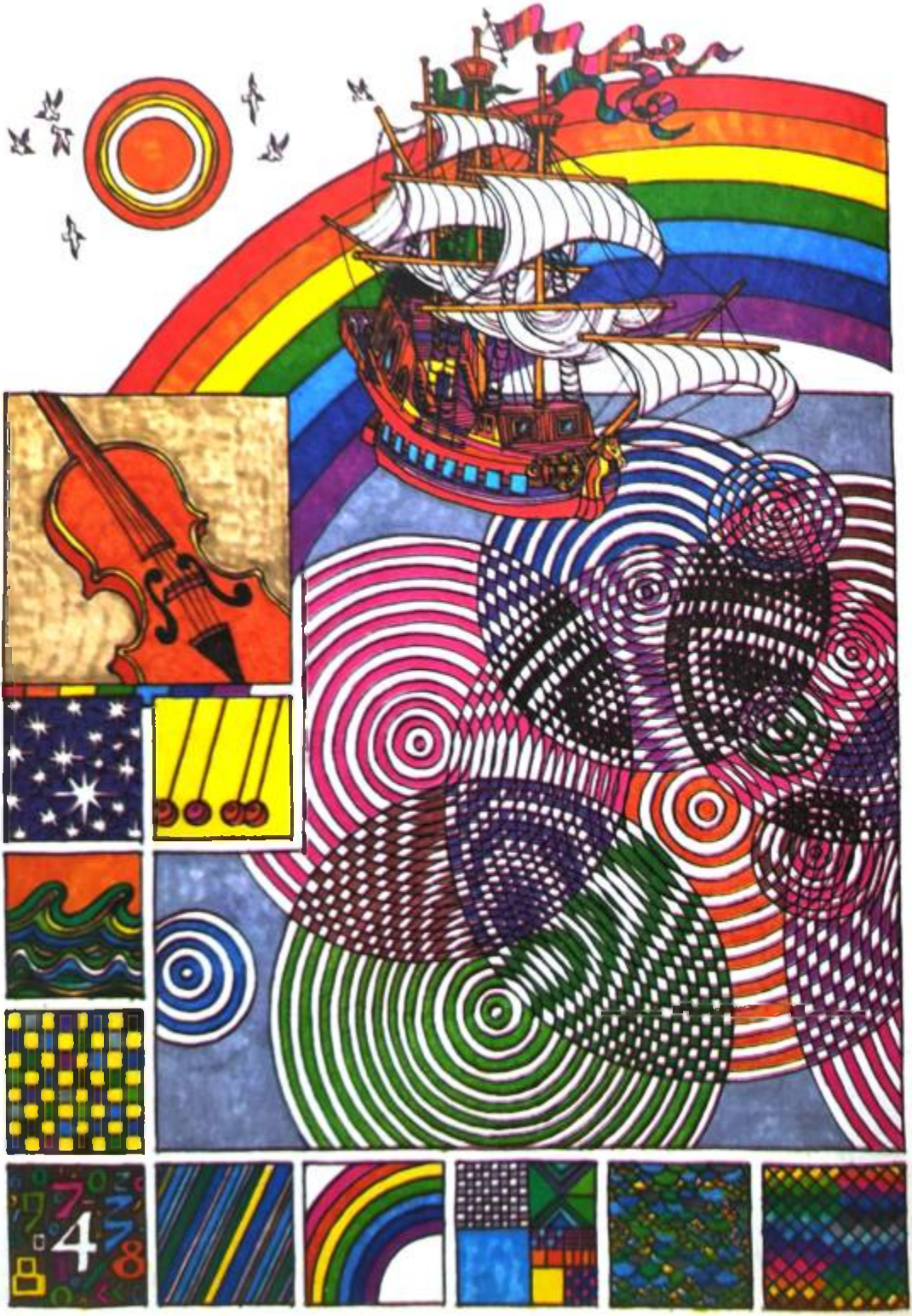
But how can you build an island in a place where it is several kilometres to the ocean floor?

A person who has gone fishing in windy weather using an ordinary float knows how difficult it is: the float bobs up and down in the water so it's impossible to notice fish biting. But if we use a narrow float, made out of a feather for example, even if there are strong ripples, it will remain as motionless as a nail sticking out of a wall. This is because its thin body does not interfere with the wave on the surface, while it reaches a depth where the wave itself does not reach. (Let us recall that the wave begins to touch the bottom when the distance to the surface becomes less than the wave's length. The same thing happens here: at a depth greater than the wave's length the wave itself is hardly noticed.)

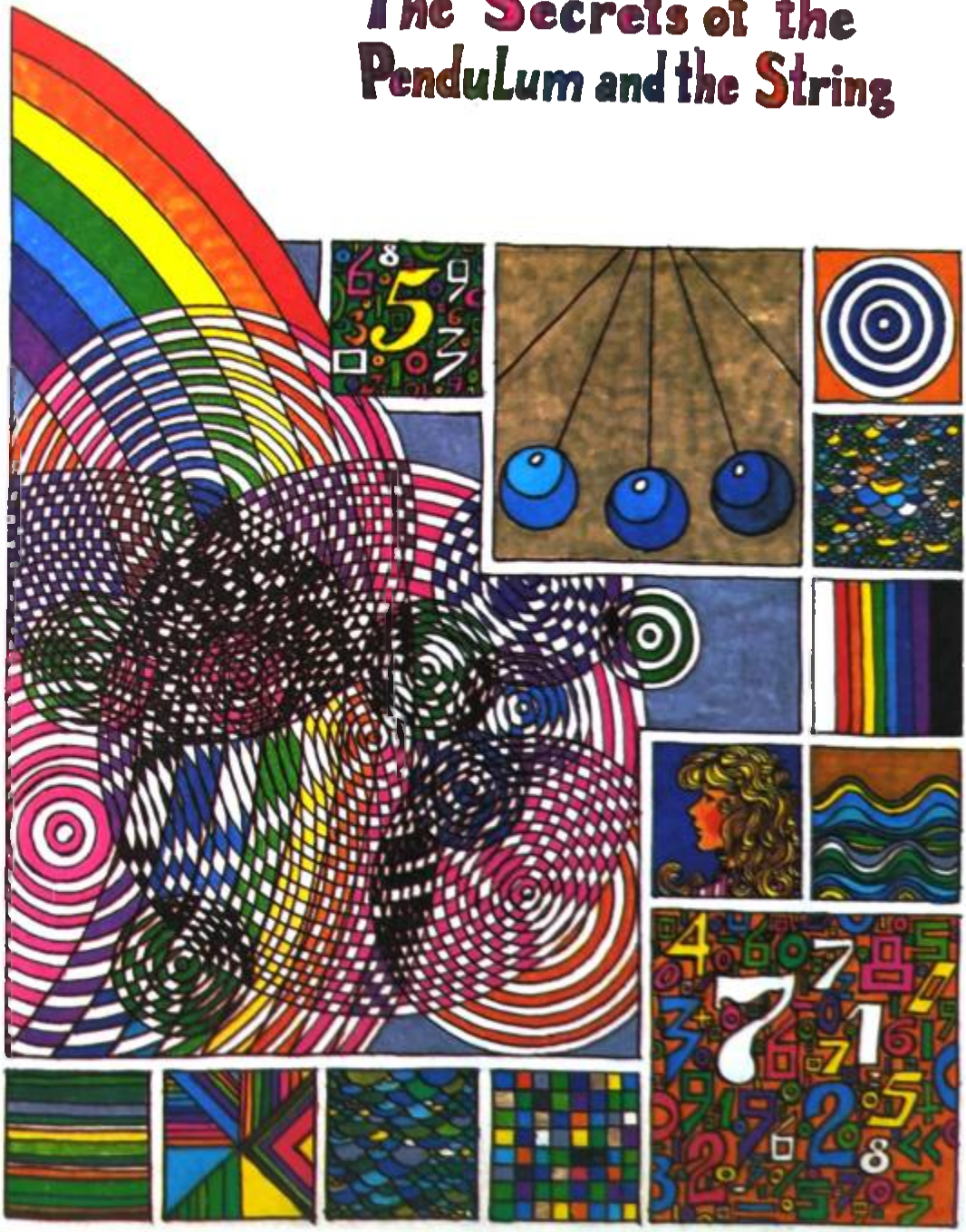
What if we build an enormous float in the ocean whose principal mass lies at a depth where the wave hardly exists? It is even better if the float is as thin as possible in place where waves rage with particular ferocity, i. e. at the surface, so the strange structure (neither island nor ship — usually it is called a floating island or manned stabilised buoy) floats in the ocean without bowing to any wave. Indeed, when such a giant thirty-storey-high structure was first built, it lived up to all expectations. During any storm the floating island stood steadfastly in the raging ocean, enormous waves placidly washing its thin neck. In the cabins

situated at heights of ten to fifteen metres above the ocean surface where the spray does not reach the portholes, the rocking is hardly felt, and it is almost as if the cabins were rooms on dry land. (This is no surprise because a wave several metres high makes the buoy swing only a few centimetres.) Oceanologists liked the islands so much that today there are dozens of steel islands floating in the ocean under the flags of different countries. They serve not only as research laboratories but also as lighthouses, radio stations, weather-observation points and many other facilities.




4

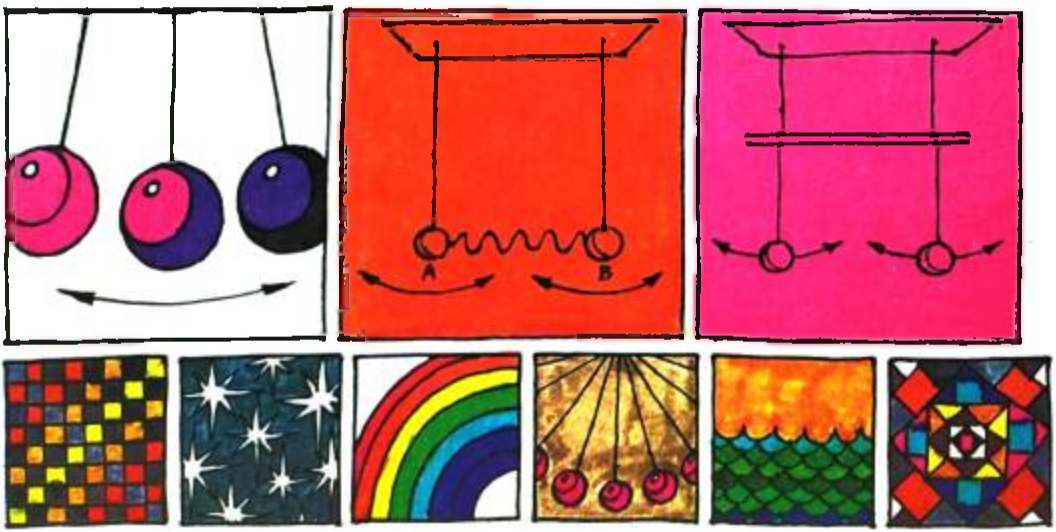
The Secrets of the Pendulum and the String



The Stubborn Pendulum

Let's stop discussing waves for a while and consider several phenomena and laws closely related to them. Here's a story that happened some four hundred years ago. One day Galileo went to church. While listening to the sermon he looked at the cathedral vaults. His attention was drawn to the huge, beautiful lamps suspended on long chains. But Galileo was not attracted by the elegant ironwork. What amazed the scientist was how the lamps swayed in the draught (the upper windows were open due to the heat). They all swayed with an inexplicable regularity, although each had its own period of motion. When we speak of oscillations, the **period** is the time in which the moving object makes one full swing — for example, from right to left and back to the starting point. Note that the period resembles the length of a wave. The only difference is that in the first case we measure time, and in the second — distance. And the resemblance is not only visible — profound meaning is hidden in it.

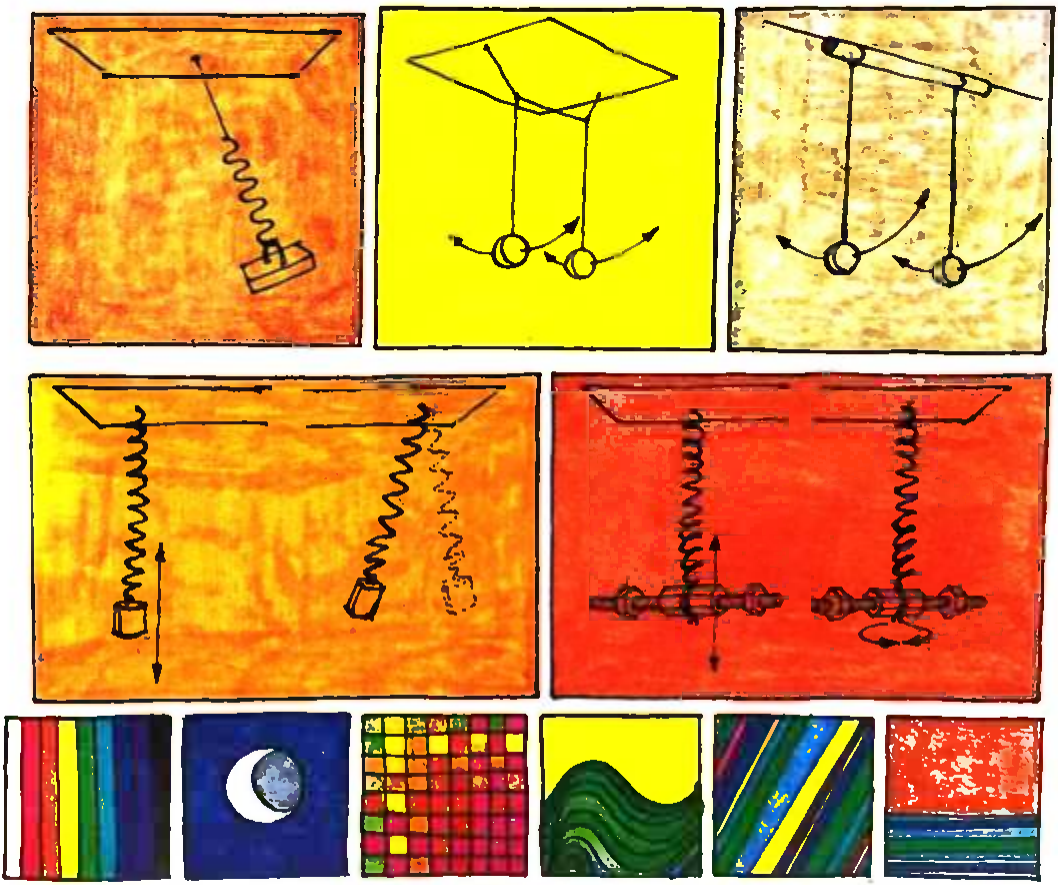
Galileo had no clock at his disposal (the elegant mechanism we call clock didn't exist at the time), but he found a clever solution: he measured time by the beating of his own heart. Holding his finger on his pulse and



watching the lamp, he noticed a remarkable pattern: the shorter the chain on which the lamp was suspended, the faster the lamp swung. It seemed even stranger to him that the periods the lamps swung did not depend on their size.

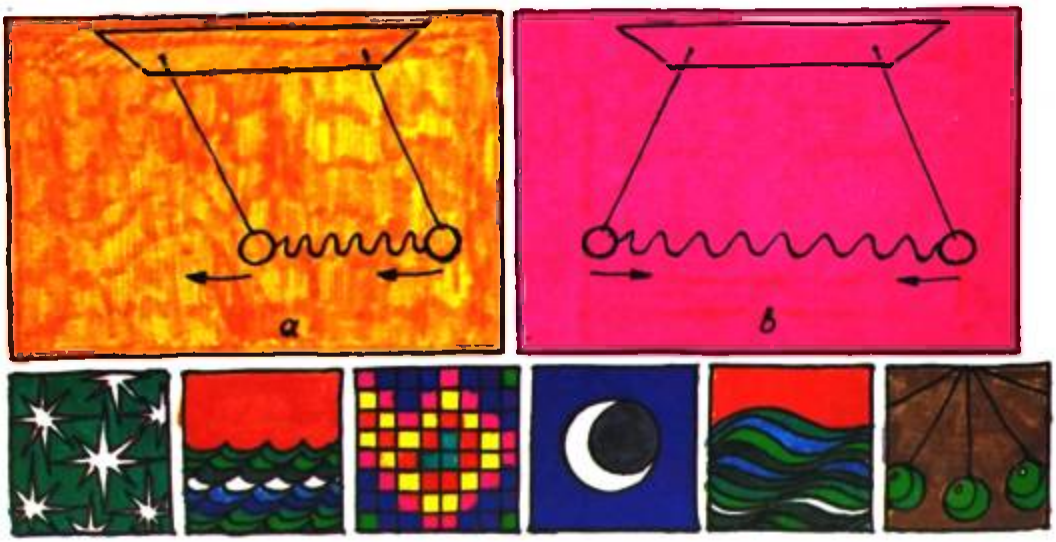
According to legend, it was in the church that Galileo discovered the law of the pendulum. The lamps he watched did not simply resemble pendulums — they have every right to be called pendulums, because in physics a pendulum is any object capable of swaying or pulsating, that is oscillating. We can even call our heart a pendulum. And the pendulum proper — the heart of any clock — was invented thanks to Galileo's discovery. But today the pendulum of a watch is small and precise.

Let us discover Galileo's law anew. It isn't necessary to swing the



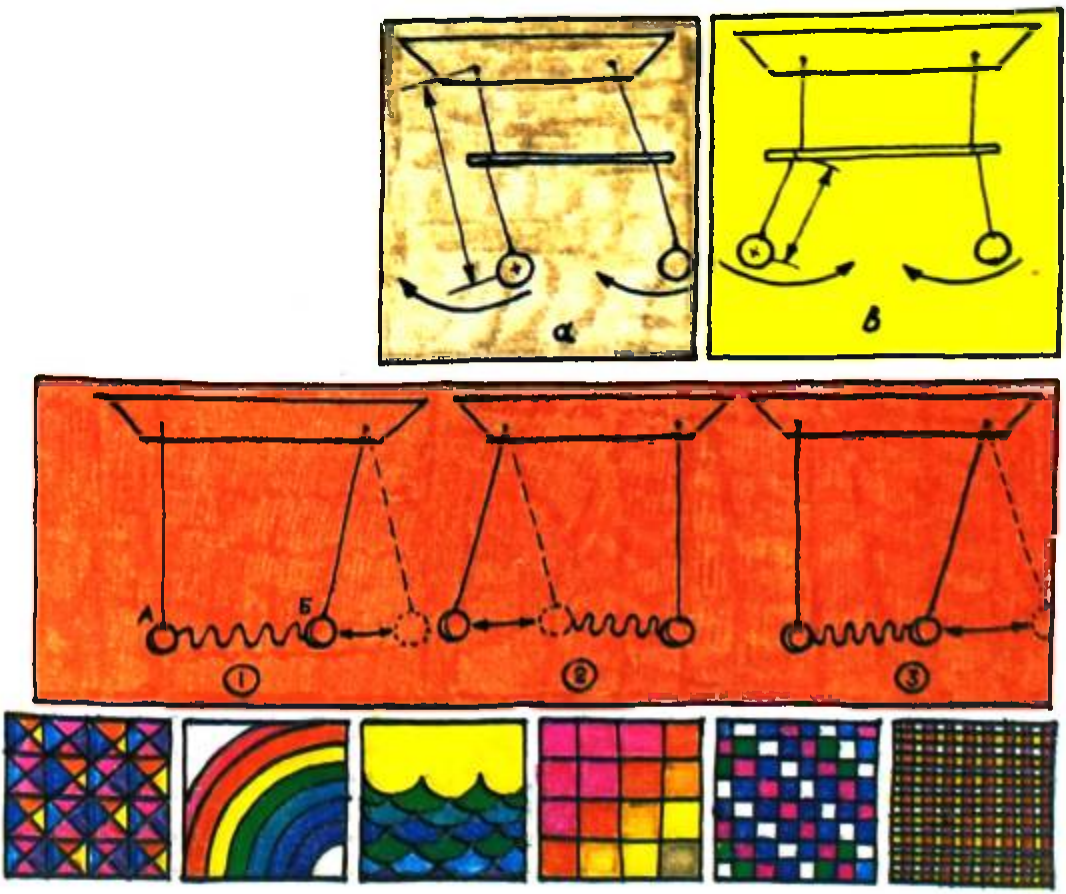
lamps in your home to repeat his observations. We can make our own pendulum. Hang an object — say an eraser — on a long string in the doorway, and make it swing (it is not necessary to swing it to the ceiling — the results are much more precise if the swing of the pendulum, that is the amplitude, is no more than twenty centimetres). Any clock with a second hand will do to measure the time. To determine the period more precisely we can measure the time required for ten full periods and divide that by ten.

So, make the string exactly one metre long, start it swinging and count the seconds (after letting go of the pendulum don't touch it any more). You can see that one swing took precisely two seconds. Now shorten the string to one quarter, or 25 centimetres, and the pendulum begins to swing twice as fast — the period is equal to one second. If the string is half a metre long the period will be about one and a half seconds and if it's two metres the period is about three seconds. Thus we have already confirmed one law: the longer the pendulum the larger the period (the time it takes to make one full swing). But the relationship is rather strange: the length of the thread changes by four, but the period only by two. Doing more experiments of this kind, measuring the time and the length of the thread more precisely, you can see for yourself that this assumption is true. Later we will return to your results again. Incidentally, we have not only discovered a law but also invented a simple and



reliable stop-watch. The principal part of the chronometer, the pendulum, is available to us, while the remaining parts of any clock, whether mechanical or electronic, are only a device to keep it swinging and to count the number of swings. Now, if you need to measure precisely a small span of time, make a 25-centimetre pendulum and it will count the seconds correctly.

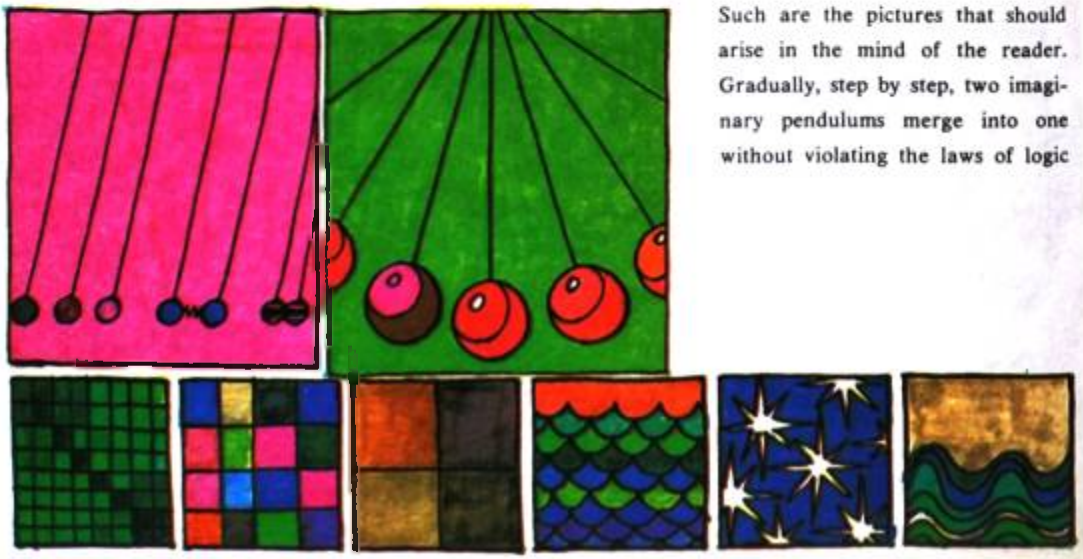
Anyone who likes swinging on swings knows how stubborn a pendulum is since, of course, swings are also pendulums. If you're strong and brave enough you can swing higher than the upper bar, but no one can change the period of the swings! No matter how hard you try, it is impossible to make the swing go faster or slower.



Let us now discover Galileo's second law for ourselves. Tie another eraser to the string — the pendulum becomes twice as heavy. Then measure the period of oscillation again. But do we really have to do this second experiment?

Long ago, when science was not called science yet, ancient philosophers checked their ideas of the surrounding world with the help of a rather complicated exercise which may be useful to us now, too. It requires a sharp wit, but occasionally helps us avoid the need to stage experiments when we want to discover or check some law. The exercise is called a "mental experiment". The experiment is staged in the mind, but the results obtained are as reliable as if we had seen them with our own eyes.

Why shouldn't we think a bit before we look for different weights to repeat the same experiment: what would the results be? First, close your eyes and imagine the swinging pendulum. This should not be difficult since we have just seen it in reality.



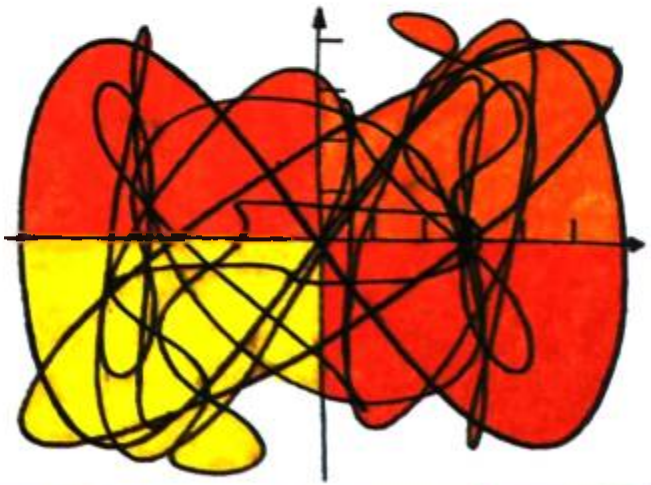
Such are the pictures that should arise in the mind of the reader. Gradually, step by step, two imaginary pendulums merge into one without violating the laws of logic

Now let's imagine that a second pendulum, exactly the same length, is hanging next to it and swinging in exactly the same way — nothing remarkable about that.

We won't be doing anything wrong if we also imagine that the imaginary pendulums are swinging in unison — moving together in one direction and then the other. Similar pendulums must have similar periods, so we can say that neither of the pendulums will swing ahead of the other.

Now get ready: the main thing is coming!

Imagine that the pendulums are connected by means of a thin thread. Nothing has really changed. They will swing back and forth in the same way. Now, having grown bold, imagine that the weightless thread linking the pendulums grows larger and stronger, filling the space between them and joining them into one. Now we have a single pendulum consisting of the two former ones and moving with the same period! Thus, with our eyes closed, we discovered the following law: the oscillation period



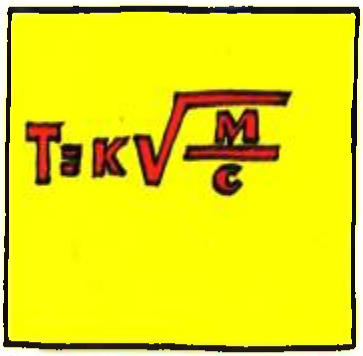
Lissajous curves

of a pendulum does not depend on its mass. What a trick! Now let's think about what happened. What happened is something only the human being can do. We engaged in abstract thinking and not day-dreaming but a logical sequence of thoughts capable of yielding practical results. For two thousand five hundred years, philosophers of the ancient world and the Middle Ages prepared the ground on which contemporary experimental science has flourished by means of such mental exercises. The principal force behind that science is not precision instruments but the keen mind, and for every experiment performed in a laboratory, there are dozens of experiments in the mind. You have seen only a small portion of the power of your mind, yet you have every reason to be proud of it. Only remember that all these exercises should be done with great care. If you make a mistake in one step, believe some trifling detail that cannot really exist, your imagination can carry you far from reality.

However, we can always stage a real experiment. Any theory must be checked in practice! To give your mind a rest and make your hands do some work for a change, let's try to get an autograph from the pendulum. In order to do this, suspend a burning flashlight on a string and put a camera under it with the lens facing up. Then switch off the light in the room, set a long exposure in the camera (long enough for several periods) and swing the pendulum slightly. The moving lamp will leave a trace on the film. Setting different exposures and swinging the pendulum in different ways, you can get dozens of different patterns. Now, if we make the base under the camera also sway, the patterns will be even more intricate. These pictures obtained as a result of two ocsillatory motions being superimposed are called Lissajous figures. The curves of these lines tell scientists a great deal about the nature of the oscillatory processes they reflect.

The Holy Number

The wise man Pythagoras lived in Ancient Greece two thousand five hundred years ago, long before Galileo. He studied different sciences — geometry, arithmetic and philosophy — but we are concerned with his study of music. Even then people knew how to make many wonderful musical instruments, although they did not understand the



Now we can no longer do without essential scientific formulas. Here we have the formula of all oscillations which occur in the world!

This can be written down in a different way: the oscillation period is proportionate to the square root of the inertia divided by the elasticity. Or: when we increase the inertia, the oscillations period increases, when we increase the inertia, the oscillations period is reduced. (Only remember that it is not a straight-line relation, i. e. when inertia or elasticity increase, say, four times, the period changes only by two.) Complex oscillating systems will also have rather complicated formulas (which may take up a whole page), but essentially they are similar to the above formula. In the case of the pendulum we experimented with the formula is quite simple: The period = $2\sqrt{\text{thread length}}$

mysteries of the sounds that made people laugh and cry. The question probably didn't even occur to them. For those who were more curious there were remarkable and instructive legends which, however, failed to provide any precise answers.

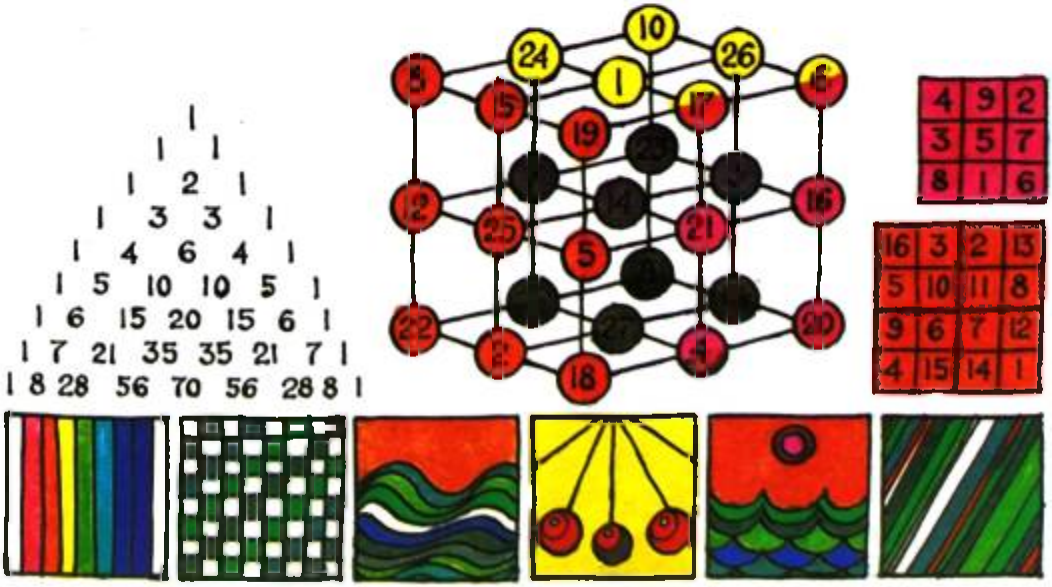
As scientists would put it today, Pythagoras narrowed the problem down. He was interested in a specific question: why were some combinations of sounds pleasant to hear while others grated upon the ears? He failed to find an answer (people still don't really know why) but reached some remarkable conclusions. Most of the sounds obtained by changing the length of a string in a string instrument, a guitar, for example, do not harmonise — it isn't pleasant to hear them simultaneously. But it is possible to obtain the few tones which sound in unison (together they seemed to flow like one sound, for example the same notes in different octaves) if the string is shortened by a whole number of times. In other words two similar strings sound harmoniously, in unison, if one is two, three or five times shorter than the other. Other harmonic accords are obtained if the relationship between the length of the strings can be expressed by a simple fraction, for example, 3/2 or 5/4 (later they were called a third and a fifth). The musical scale constructed according to these laws of absolute harmony has come down to us, and is known as Pythagorean Scale.

The strange but indisputable relationship between prime numbers and musical harmony, pleasant emotions and mathematics fascinated Pythagoras and his pupils to such an extent that they began to worship a peculiar god, The Holy Number. It seems silly, of course. Nevertheless, modern science, with all its formulas and thorough understanding of many natural phenomena appeared thanks to these rather naive ideas of the

Pythagorean school. And the belief held by some of our contemporaries that all phenomena can be reduced to a formula is, perhaps, an echo of Pythagoras's faith in the magic of numbers.

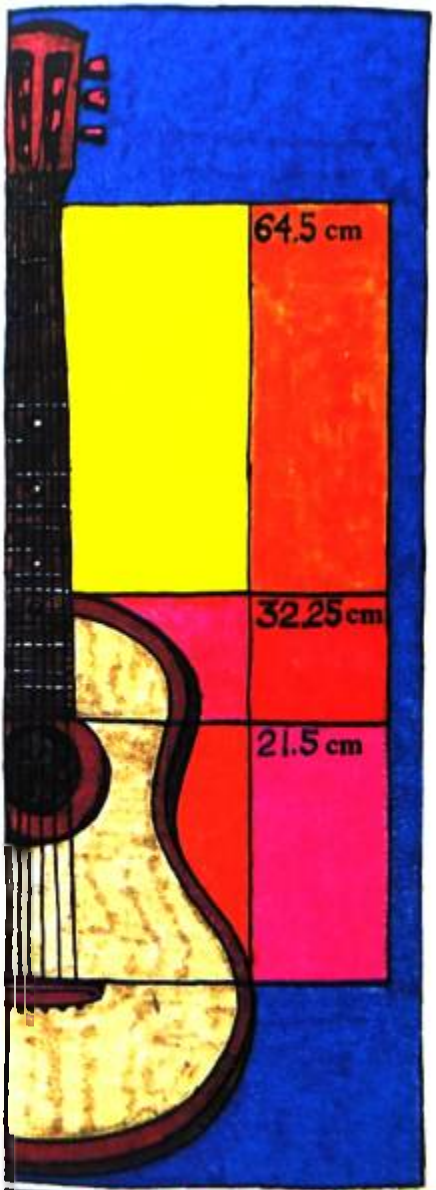
But what do Galileo's discovery and Pythagoras's experiments have in common? And what do they have to do with waves? We'll learn the answer a bit later, but meanwhile let's ask a few questions ourselves.

You already know some of the laws of oscillation. But can we explain why they are the way they are? It's not enough to say that a law is a law and there's no need to attempt to explain it. Although occasionally such an answer proves to be the only one as yet, we are often able to penetrate the mysteries of natural phenomena that have not been fully understood, and discover the secret mechanism which make nature behave in the particular way that it does. A whole theory has been developed for pendulums explaining how they swing. The theory says that two qualities confront each other in every pendulum: slow, heavy inertia on the one hand, and a restoring force on the other. The stronger the former quality, the slower the pendulum swings. If the latter quality is



more pronounced, the pendulum swings faster. In Galileo's pendulum both these qualities are similarly related to the mass of the weight. Since it swings, the string may also be regarded as a pendulum. Here inertia is related to the mass of the string, while the restoring force depends on how tight the string is. Everything falls into place when we adopt this view. If the weight on the string is doubled, both the inertia and the restoring force will be twice as great. Neither of the qualities overshadows the other, and the pendulum behaves as it did before. If the string is cut in half, its mass will be reduced by half, the inertia will be weakened correspondingly but the string will remain just as tight. Then the string will swing faster. Everything seems clear! But if you're stubborn enough, you'll ask a thousand more questions. For instance: why does the weight's mass influence both conflicting qualities equally? Or: why is it pleasant to listen to sounds when the frequency of their vibrations differs two or three times?

Why, indeed? It turns out that both these questions lead the researcher into the very heart of the science of matter and the sciences of human physiology and psychology. And neither question can be answered as yet. Such is the sad lot of scientific theories: the more that is explained, the more questions arise until, finally, there are questions the theory is still unable to cope with. It is at this point that the scientist needs real fortitude not to avoid questions which still have no answers, not to invent false explanations when the true causes are unknown. He must always hope that the next step will be taken if not by him, then by those who come later and who will understand where the mistake was made.

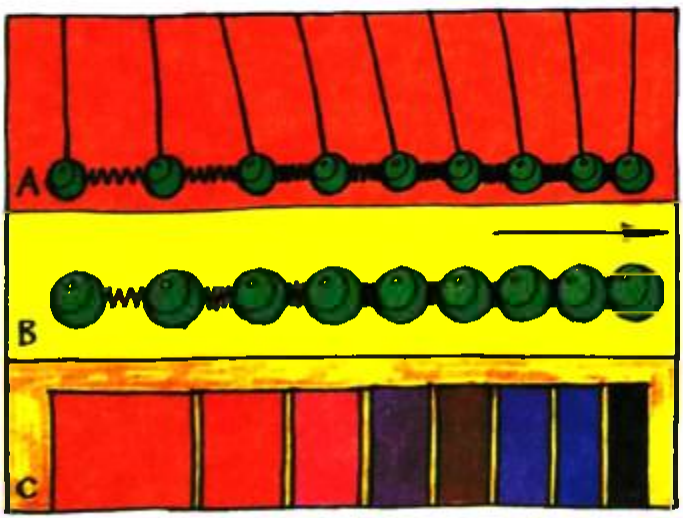


The modern guitar does not differ in design very much from the cithara played by the ancient Greeks. If we pick three of the most consonant notes on one string (for example, a C, then a C an octave higher and a G on the same octave) and measure the length of the free string, we will find that we shortened the string two and then three times. Once again we face the magic of ordinary and precise numbers! In other words the relationship of lengths is 1 : 1/2 : 1/3

Underground Waves

Now let's take another important step. Imagine many, many pendulums hanging in a row and all of them linked by springs. Push the pendulum on one end. It will swing once and stop, because its energy will be transferred to the next pendulum which will also swing once and push a third pendulum. This will continue along the row. Doesn't this remind us of something familiar? It is essentially in this way that waves move along the surface of the water. Only the wave moving along the row of pendulums is called an elastic wave. Such a wave moves even better through a solid object — a piece of metal, a rock or...

...Or deep inside the Earth itself. These are the seismic waves mentioned in the chapter on tidal waves. These waves are always moving under the ground — but can you feel the earth trembling underfoot? They can hardly be felt if there is no real earthquake. Usually the size of seismic vibrations is very small, and it is necessary to use very intricate devices called seismographs to perceive them. These devices are so sensitive that if they were put in an ordinary house they would



A. A wave runs along a chain of pendulums connected by springs. As in the case with the sea wave the pendulums eventually remain in the same place, so this wave is a travelling form incapable of carrying away a single material particle.
B. If the pendulums do not have threads (when the loads, for example, lie on a very slippery surface), nothing will change: they will elastically transmit the agitation they have received, themselves remaining in place.
C. There are no springs here between the pendulums but they are pressed to each other closely, the kick will thus be transmitted due to their own elasticity. Thus, we obtain a monolith or solid inside which an elastic wave runs

respond to the steps of someone walking along the next street. It is possible to receive news from the farthest corners of the Earth by means of these devices provided they are in hermetically sealed cellars or deep shafts. The needle of the recorder jerks, leaving a crooked line on the paper roll, and a trained person can later decipher the recording and tell where the earthquake is occurring and even measure its strength. If the earthquake proves to be somewhere in the ocean, all the towns and cities on the coastline will be warned of an approaching tsunami. The deadly wave will be discovered almost immediately after it arises. This is why seismic stations are on the alert round the clock.

Earthquakes are not the only things which can be detected by means of seismographs. The seismograph is also capable of recording Earth tremours arising from an explosion, so it is impossible to explode a nuclear bomb or even launch a missile without it being noticed at seismic stations all over the world.

The seismograph is useful in geology as well. With it geologists no longer have to drill deep shafts to find mineral deposits. It is often enough to listen to the Earth as a doctor listens to a patient's chest. Of course the Earth cannot be prodded or poked, but if we explode some dynamite in a shallow shaft, a mobile geological seismograph located nearby can record how the wave changed as it travelled from the explosion site and determine what layers lie at what depths. In the same way geologists probe the Earth in the places where dams or large industrial plants are to be built, so construction workers erect them of firm ground. There have been unfortunate cases when construction work had to be stopped because the ground proved to be too weak.

It is possible to listen to more than just the Earth in this way. In a china shop, the sales clerk will tap the cups and plates softly before packing them to see how they ring. If there's a hidden crack in the plate, the sound will be unpleasant and jangling. An expert can not only discover a crack by the sound but also judge the quality of the china. Not only cups and saucers can be checked in this way. Various metal parts are checked at plants, particularly if the parts are molded in one piece and you can't look inside them. Of course they are not listened to with the human ear but with special devices similar in operation to the seismograph.

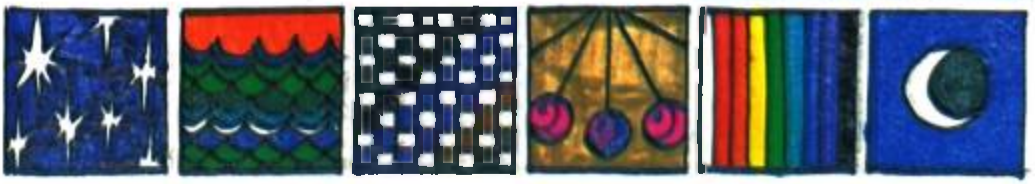
Hunting the Invisible

Practically any object can vibrate. Only the amplitude of the vibrations is so small (hundreds of a millimetre) that they are not visible to the naked eye. But the German physicist Chladni, who lived at the end of the 18th century, managed to do without precision optical instruments by using his intelligence. He reasoned as following: it may not be possible for us to see the vibrations themselves but, perhaps, some other phenomenon will tell us about them. Let's repeat Chladni's experiment. Fix a

metal plate the size of your palm horizontally in a vice. If you run a file over the edge, it will grate on your ears. This means the plate is vibrating. Now sprinkle some fine sand on it. If we run something along the edge again, the sand will form a complicated pattern as if by magic. Run the file along the other edge, and the patterns will change as if in a kaleidoscope. These figures have been named after their discoverer, Chladni. They reflect the shape of the plate's vibrations: the sand is shaken off the vibrating parts of the surface to the places where the vibrations are weaker. In this way the key lines appear on the plate: the places which do not move during the vibration of the whole plate.

The vibrations we managed to see thanks to the sand patterns are an interesting intermediary stage between the swinging of the pendulum in

The hero of a science-fiction novel was saved because he happened to drop cigarette ashes on the floor of the spacecraft cabin (the author thought that astronauts would smoke for some reason), the ashes formed Chladni figures indicating the otherwise invisible vibrations. (Technically speaking vibrations are elastic oscillations in solids.) However, vibrations are analysed in life as well by means of Chladni figures: machine parts subject to strong vibrations are studied in this way. The classical Chladni figure is shown in the drawing on the left. However, it is quite impossible to investigate the vibration of parts with a complicated shape by means of sand or ashes. It is another thing if we light up the part with a laser beam. On the right is a photograph made in laser light: it shows the distribution of vibrations on the blades of a ship's screw propeller. An experienced researcher can spot the area of a defect



a working clock and the vibration of the particles in a wave constantly moving somewhere. Here, the wave is locked within a small plate. It is called a standing wave. The crest and the trough replace each other rapidly, but the wave itself doesn't move anywhere.

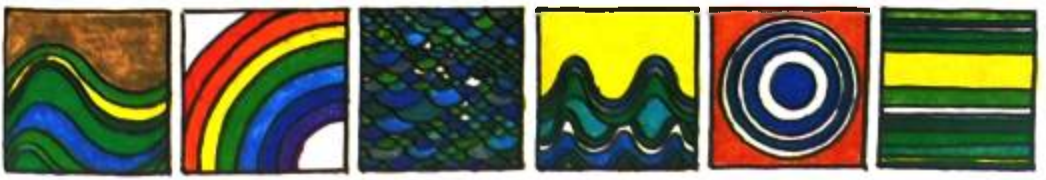
But why does the plate on which we obtained Chladni figures rattle so loudly? Why can we hear vibrations which even the eye can't distin-

Chladni figure

guish? It turns out that the vibrating object transfers its vibrations to the air surrounding it. Therefore the sounds our ears hear are also elastic waves moving from the vibrating object through the air.

American inventor Thomas Edison already knew about the relationship between sound waves in the air and the vibration of solid objects. This helped him design an original machine which we can find today in an altered form in almost every home. It was the phonograph, which was later called the gramophone after the design was changed, and in our day is the record-player.

In Edison's machine a steel stylus slipped along an uneven groove on the tinfoil surface of a revolving cylinder. The vibrations from the uneven groove were transmitted through the stylus to a metal diaphragm which transmitted the vibrations to the air. As the zigzags of the groove repeated the vibrations of the air produced by a human voice before a microphone, the phonograph could repeatedly reproduce words pronounced long before. The sound was recorded by means of the same device. The same stylus transferred the vibrations of the diaphragm caused by sounds to the groove on tinfoil. Later sound was recorded on a more pliable material, a wax cylinder, and it became clearer and louder, although the recording proved to be less durable. Today, transmitting sound to a record has become a complicated multi-stage process, but the record, just like the phonograph cylinder, has hundreds of grooves on the surface whose unevenness retains the memory of air vibrations which once occurred at the recording studio.



Technology Without Science

For a long time people have known how to make various intricate devices although they had only the vaguest ideas about the laws of Nature. Take musical instruments made by the old masters — the warm and inspired voice hidden in violins dark with age fill the present-day connoisseur with admiration and amazement. Then why should we bother studying and investigating Nature if a person can do his job without science? Indeed, violins from the workshop of Antonio Stradivari, the

Stringed musical instruments of different ages are remarkably similar. Their shape changed with the centuries, but the changes were made not to alter the sound of the instruments, but rather due to fashion. Thus, the elegant shoulders of the modern violin are merely an echo of the baroque style which appeared in the 16th century. The real development of musical instruments, enrichment of sound providing new opportunities for the performer, occurred very slowly. The violins on the drawing date back to the 17th and 18th centuries, but they hardly differ from modern ones

famous 17th-century Italian master, are still unrivalled. But few people think about what was involved. By means of trial and error, wasting countless years, whole generations of craftsmen sought the best shape for their instruments and searched for improved work methods. Each of them improved only slightly on what his predecessors had done. A competent engineer, drawing on the knowledge scientists have gained, can cover the ground, which formerly took centuries, in a matter of years.

We see the same thing in shipbuilding. It took hundreds of years for the clipper ship, the best of sailing vessels, to appear. Throughout this period the clumsy, slow galleons and frigates hardly changed at all. Not really knowing the laws by which waves move and ships behave on those waves shipbuilders dared not introduce bold changes into ship design.

If we are speaking of developing something new and not of gradual improvement, it is impossible to do without knowledge. And not just knowledge but a deep understanding of how Nature behaves, the knowledge that is now called science. Indeed, Edison's phonograph was such a simple device that it could have been made by a medieval mechanic or even a blacksmith living in ancient Rome. But the device was invented only after people gained a better idea of the laws of sound waves.

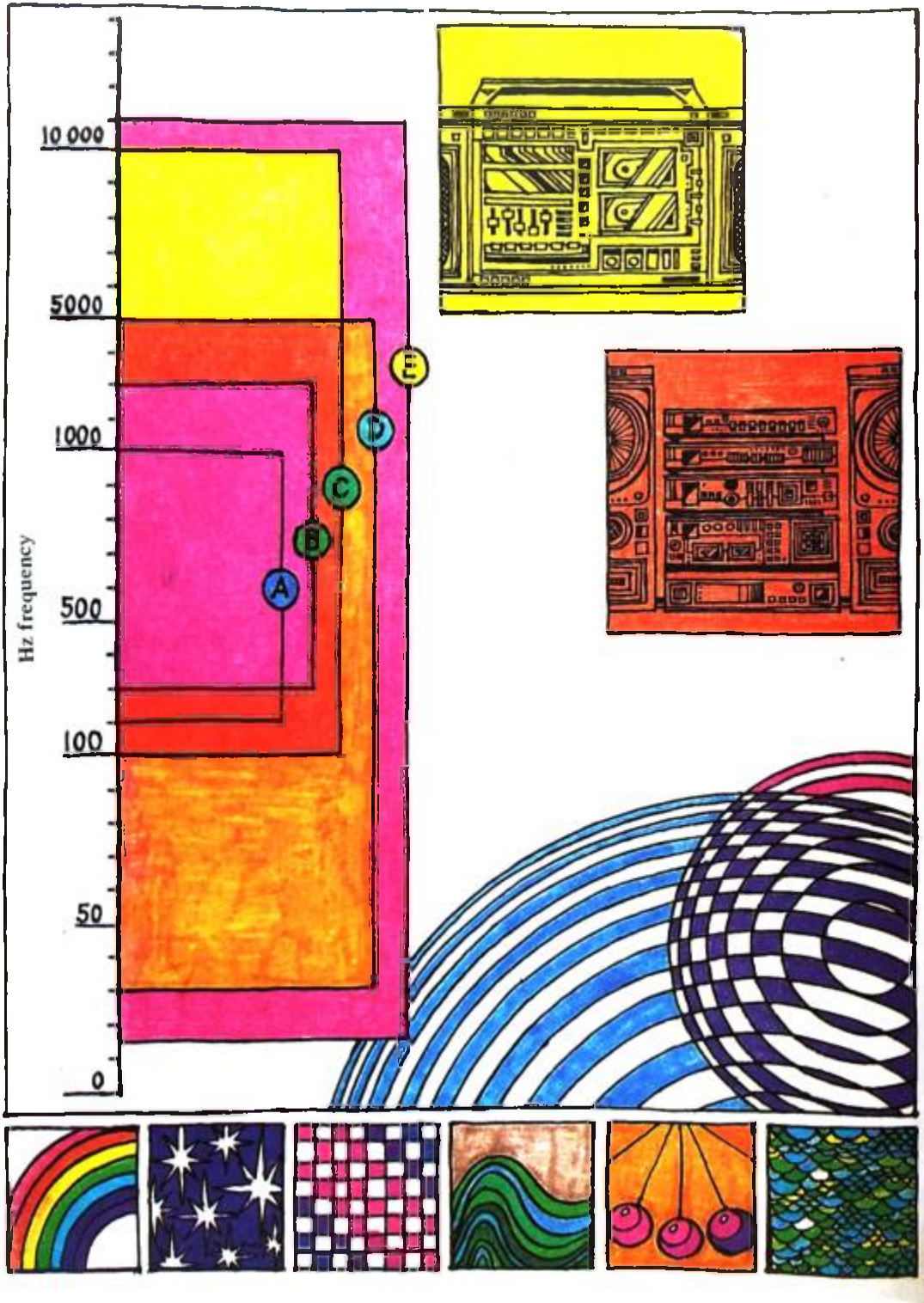
Let us return to the account about waves however. Just as people did for many centuries, you take advantage of many laws of sound, even if you know nothing about them. You cup your mouth with your hands to make your voice carry farther, but do you know that in this way you are forming a simple megaphone, a device used at sea and in battles?

Sound usually spreads from its source in all directions, and the farther it goes the larger the space through which its energy spreads. Only an

insignificant part of the waves produced by the force of our lungs reach the listener. When a megaphone is used, the sound moves only in one direction, and will retain a much larger part of the initial loudness upon reaching the listener. A megaphone works much like the focussing device in a flashlight. If we remove the reflector from the flashlight, the lamp seems to burn much less brightly. Today electronic devices are used to amplify sound and the old-fashioned megaphone is being forgotten, but recently that simple funnel-shaped device could still be seen on a ship's bridge, a boat-house and at a stadium. On a ship there was a communications system in which the sound is directed into a narrow pipe so its energy

Here is another example of the blind groping of human thought. A sail on the bow was formerly called a spritsail. For thousands of years vessels had sailed without them, but then someone had tried to fasten it in the position shown, and the ship sailed much better. A century later it disappeared from the rigging of ships, it turned out to be rather inconveniently located too low over the water, and it was frequently torn off by high waves. Then it was introduced again but higher (it began to be called an upper spritsail), yet it failed to live up to hopes. Later its place was taken by a very simple jib which has come down to our day

is not dissipated throughout the surrounding space. On large vessels the captain could transmit orders quickly to the engine room or the crew's quarters because the rooms were connected by pipes resembling plumbing. Only there were whistles instead of faucets at the ends of the pipes. When the captain wanted to talk with the mechanic, he blew into the pipe and there was a shrill sound in the engine room. After taking the whistle out of the pipe, the mechanic put his ear to it and heard the captain despite the roar of the ship's compartments. Replacing pipes by wires has not changed the basic principle. The electric current running in the wires operates according to almost the same laws as air waves in a pipe, but more about that later.


10 000
5000
1000
500
100
50
0
Hz frequency
A
B
C
D
E

The Ladder of Sounds

Now we will discuss waves which can be heard but not seen — sound waves. However, not every sound can be heard. The human ear can detect only a small part of all sound vibrations existing in Nature. The sound must not be too soft or too loud, or too high or too low. And each of us has his own ideas about sound. For example, some people are overwhelmed by the chirping of grasshoppers on a summer day in the field, while others think it is very quiet there. This is easily explained:

The frequency of oscillations is nearly the same thing as the amount of time they take up. If, for example, the oscillation period is a hundredth of a second, i. e. there are a hundred oscillations a second, it is more convenient to say: the oscillation frequency is 100 hertz. The words hertz and kilohertz (thousands of hertz) are quite common today. They express important specifications of electronics equipment found in any home today. The instructions of a tape-recorder, record-player or radio-set always point out the frequency of sounds the equipment is capable of reproducing. Let us see what place on the sound frequency range ordinary sources of sound take (drawing on the left). The letter **E** designates all the sound frequences heard by the human ear, the letter **A** the range of the usual human voice. The voices of musical instruments occupy a slightly wider range which is marked by the letter **D**. Now let's see what ordinary electronics equipment which reproduce sound is capable of.

THE TELEPHONE. Few people would think of listening to symphonic music over the telephone, and a range from 200 to 3.000 hertz (the letter **B**) or even less is sufficient to distinguish words. Of course the voice sounds toneless and not very expressive, but the most important thing is to understand what is being said.

THE TRANSISTOR SET. It is too small to produce really good-quality sound, but it can reproduce the full range of the human voice and music. A quality transistor has a frequency range from 100 to 10.000 hertz (**C** on the scale). Yet as music-lovers say, the sound is rather poor: it lacks the natural sound of musical instruments.

For that reason we have HIGH-QUALITY SOUND EQUIPMENT usually marked Hi Fi or High Fidelity. All the components — complicated electronic circuits, large loudspeakers, and a record-player resembling laboratory devices — are designed to provide authentic sound. The frequency range is often even wider than the human ear can hear: say, from 15 to 50.000 hertz and music and speech sound so realistic, they cannot be distinguished from real music and speech

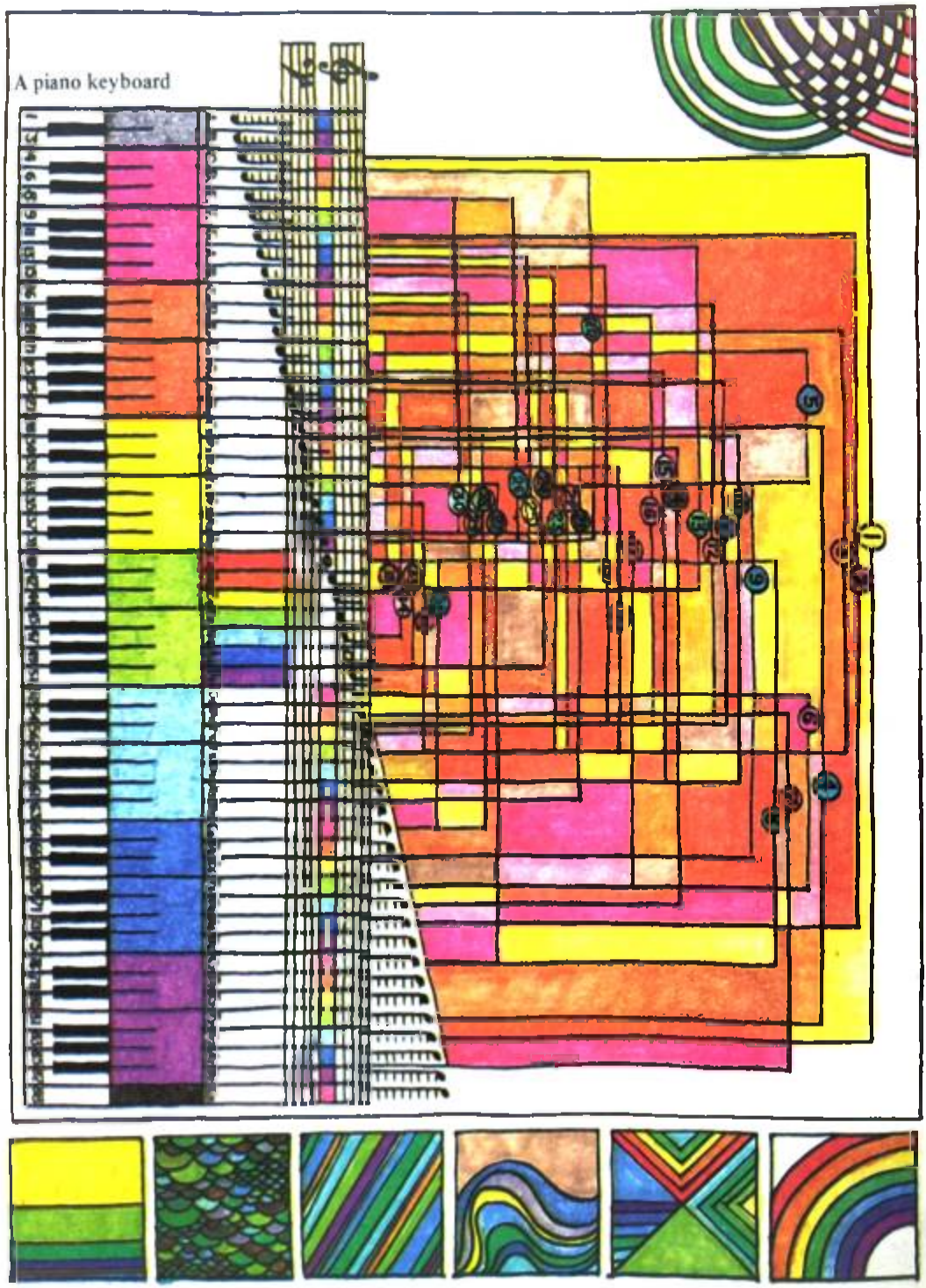
different people have different limits of audibility. Officially, sounds audible to the human ear range from frequencies of 16 hertz to those of 20,000 hertz (a hertz is one cycle per second). If we take the sounds produced by a piano, the lower limit of our hearing lies slightly lower than the bass note, while the higher is a good deal above the highest one. Sound waves with a frequency below 16 hertz are infrasonic while those higher than 20,000 hertz are ultrasonic. (The Latin prefixes infra and ultra mean lower and higher.) These inaudible sounds merit special consideration.

It was suspected a long time ago, that extremely low sounds existed, but no technical application was found for them. Interest in them was renewed only in the last few decades when scientists began to study not only technology but the human being as well. It was discovered that although people could not hear these sounds, they felt them in some way. These low sounds provoked various emotions, always unpleasant ones, or at least a feeling of alarm.

Once the Swedish film director Ingmar Bergman submitted viewers to an interesting although slightly cruel experiment. A short film he had made was shown in an ordinary cinema several times: a little girl was picking flowers and singing a song for about ten minutes on the screen. At the first showing the film was accompanied by pleasant music, but at the next showing infrasound was added. When the viewers were subsequently asked to share their impressions, some who were at the first showing said that they had a radiant, happy feeling while others said they were bored. But the viewers who watched the film with infrasonic accompaniment were amazed by the director's ability: the most ordinary sequences had provoked a feeling of alarm! When the volume of infrasound was raised at the next showing, the result was remarkable: the viewers fled from the cinema hall in panic. How can this be explained? There is no definite answer yet but one interesting hypothesis does exist. It has been observed that infrasound usually arises in Nature before some

danger or catastrophe. It is produced by strong winds, earthquakes and forest fires. Perhaps, in the course of thousands of years, natural selection has taught people and animals to distinguish signals of alarm? When there is serious danger, the feeling of fear is more effective than any other emotion. Only that feeling forces both humans and animals to flee from the unknown danger without hesitation. This hypothesis is supported by instances when animals warned of an impending catastrophe — their perception is sharper than in humans. Anyone who has observed a storm from the shore may remember vague feelings of admiration and alarm which seize a person.

People have not learned to use infrasonic waves yet. Someone has proposed to make an infrasonic weapon sowing panic among enemy soldiers so all of them flee in fear. But since these waves travel everywhere, it is not clear where "our men" are to hide from the fearful music. While it is not known whether infrasonic waves can be put to use, it is of the utmost importance that we learn to avoid their harmful effects on the human body. It has been discovered that many machines and industrial plants generate strong infrasonic vibrations. It is particularly dangerous when these are emitted by automobile or airplane engines. The driver or pilot becomes tired very quickly, is seized with anxiety, and this may lead to an accident. It is equally bad if operating machine tools produce infrasonic waves: productivity falls and not only among those who are working on them but also among everyone else nearby. It's very bad if the ventilation system of a residential building produces these vibrations: the people who live there will become irritable and will fall ill more often. To protect people from the harmful effects of infrasonic waves, scientists have developed special infrasonic microphones, and no machines are permitted to operate without being checked for infrasonic emissions.


A piano keyboard

The sound range of musical instruments and the human voice (figure on the left)

1 Harp

2 Accordion

3 Guitar

4 Marimba xylophone

5 Kettledrum

6 Bells

7 Piccolo

8 Flute

9 Soprano saxophone

10 Alto saxophone

11 Tenor saxophone

12 Baritone saxophone

13 Bass saxophone

14 Clarinet

15 Alto clarinet

16 Bass clarinet

17 Oboe

18 English horn

19 Bassoon

20 Bass bassoon

21 Cornet

22 Alto trombone

23 French horn

24 Trombone

25 Tuba

26 Tuba

27 Violin

28 Viola

29 Cello

30 Bass fiddle

31 Soprano

32 Alto

33 Tenor

34 Baritone

35 Bass

Putting Sound to Work

People are quite deaf to ultrasonic waves, but many animals hear them very well. If we make an ultrasonic whistle (no more complicated than an ordinary whistle), it is possible to give commands to a dog, and no one (except other dogs of course) would be able to hear them. Some animals such as bats or dolphins possess an even more interesting ability. Hunting in total darkness, they use their natural ultrasonic devices instead of sight. Squeaking continuously and listening to the sound reflected from surrounding objects they easily find their prey.

Back in the 18th century it was theorised that bats use hearing in order to find their way in space. The fact was proved by means of original experiments. Several bats were put into a completely dark room criss-crossed by thin strings with little bells. It would be difficult for birds to

The portrait of a bat. Its enormous ears are like speaking-trumpets which catch the weakest echoes of its own squeaks

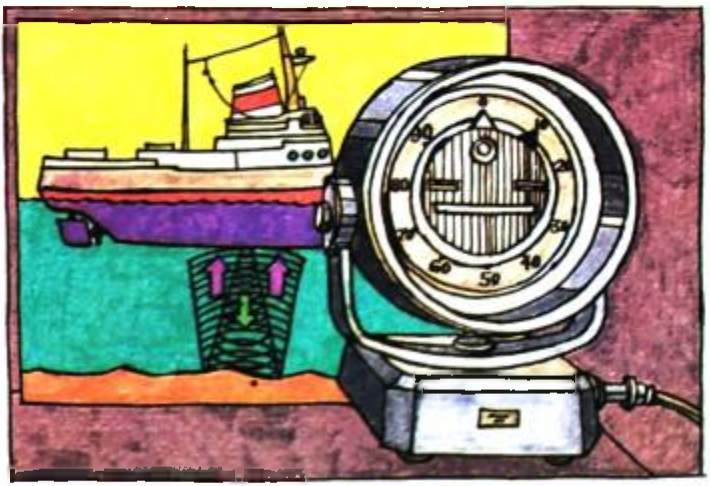
fly in such a place in broad daylight, but the bats hunted gnats easily without making a single bell ring. The researchers tried to blind the bats, shielding their eyes with special "glasses", but the bells remained silent. Hoods of a thick fabric were pulled over their heads (some believed the bats felt their way by means of their fine whiskers), still there was silence in the room. The bells began to ring only when the bats' ears were stopped up with wax: the bats flew around the room without noticing the strings.

A century and a half later, when people learned to make ultrasonic microphones, the theory explaining how bats saw in the dark was confirmed. The squeaks heard by means of these instruments proved to be remarkably loud: their level was comparable to the noise of a subway train in a tunnel. A natural question arises: why had the bats resorted to ultrasound? Perhaps they are simply unable to produce low sounds. But Nature is usually guided by more important considerations. Calculations show that the sounds we hear spread in metre-long waves. These waves are hardly reflected from a gnat no larger than a millimetre. A sound with a frequency of more than 30 kilohertz has a wave shorter than a centimetre and a gnat would be quite a serious obstacle for it. Ultrasound has another advantage: it is easier to focus it in a narrow beam than lower frequency sounds.

The properties of ultrasound useful to bats have made it a good helper for people. An echo-sounder used to penetrate the sea depths operates according to the same principle the bat uses to catch its prey. Moreover, ultrasound is being used as a tool-maker thanks to its ability to be focused

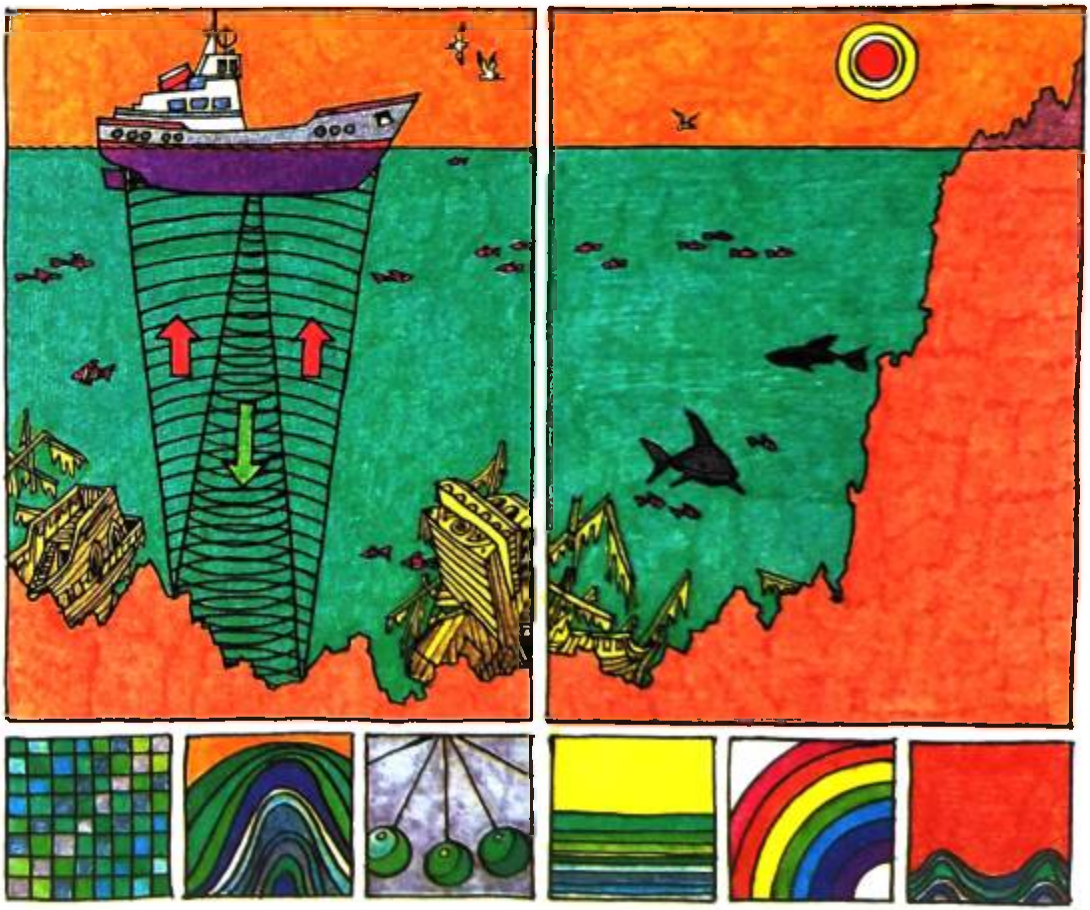
into a thin ray. Do you remember the fun you had with a magnifying glass? The lens directs ordinary light which brings little warmth into one small point, making wood or plastic burn. If ultrasound, inaudible to us is focused on one point by means of a special device which, however, is not at all like a lens, the energy of this ultrasonic drill is so great that it makes tiny well-shaped holes even in metal. And ultrasound displays its talents in almost every industrial plant: it washes bottles, clears the rust off metal, or paints finished parts (and better than any brushes).

For many hundreds of years, sailors measured the water depth with a sounding line. The line was thrown overboard and lowered until it touched the bottom, and the depth was determined by the markings on the line. Modern lines, or echo-sounders, measure the depth by means of ultrasonic sound much more precisely and quickly. The echo-sounder consists of a transmitter and receiver installed on the bottom of the ship's hull, and the device itself is installed in the wheelhouse or a special asdic-room and constantly records the irregularities of the sea bed under the ship



The echo-sounder

If an ultrasonic ray is aimed at a vessel with different liquids, it mixes them together in one minute better than you could do in a week. Chemical industries began to use ultrasound to mix chemicals and make paints. Then another advantage of it was discovered: after it mixes liquids, there is not a single microbe left — the microbes are unable to survive the ultrasonic vibrations. Ultrasound thus serves biologists and doctors: it is better at disinfecting water than boiling or using substances to kill the microbes.



Traces of Mysterious Animals

It is interesting that after we considered waves in a solid body — the depths of the Earth — and sound waves in the air, we passed over to ultrasound, or elastic waves, working in water. The waves we spoke of at the beginning of the book are not the only ones to exist in water. Sound waves are also located there, just as they are in the air. The idea that silence reigns in the depths of the sea comes from the fact that sound does not easily pass from water into air. Also our ears are not made to hear well underwater. But anyone can make a good "underwater ear" himself. Take an ordinary rubber bulb from a syringe and attach a long rubber tube to it. Now if we lower the bulb into the water and put the end of the tube to our ear, we will realise what a lot of different noises there are under the water. Incidentally, oceanologists use similar "underwater ears" which are called hydrophones. If we listen carefully to the voice of the sea, we can hear the roar of a distant storm, the sounds of a steamship passing by and even the conversation of sea creatures. Many

Researchers have called the deep-water sound-conducting layer SOFAR. Soon it will be put to use serving people. For example, the sound of a distant earthquake travelling along it will enable coastal inhabitants to be warned of an approaching tsunami

of them are very talkative despite the fact that people think otherwise. Some, like bats, use their voices to find their bearings in the darkness of the depths, others talk with one another, while still others seem to make noises simply to express their joy of life.

There is a small fish in the ocean — the sea catfish — with a voice louder than that of many deep-sea giants. When they gather in schools and strike up a concert, which sounds like frogs croaking, the noise is so great that underwater mines set to explode at the sound of a ship's propellers go off. Some kinds of sea shrimps also like to raise a ruckus. A large number of these little creatures snapping their pincers makes a noise as loud as the sea catfish.

Researchers listening to the ocean depths are like unexperienced urban dwellers in the jungles at night. One day an oceanologist named Barni managed to record the voice of a creature, yet the identity of this creature (known as Barni's animal) remains a mystery to this day.

The world of sounds in the ocean is best known by sailors on submarines. At depths untouched by light, where radio communications are impossible, sound is the only thing enabling the submarine to determine the correct course and to find an enemy vessel. No wonder the soundman on a submarine is held in such high esteem.

Recently a sound miracle was discovered in the sea depth. It was found that in all the oceans there is a special layer at a depth of several hundred metres in which sound spreads but remains within the layer. If we take into account that in water sound weakens much more slowly than it does in the air (one doesn't always hear a cannon shot at a distance beyond ten kilometres on land, while the sound from the explosion of a small dynamite charge underwater travels hundreds of kilometres), it becomes clear that voices from all parts of the World Ocean can be heard in the sound-carrying layer. Having discovered this miracle of Nature people began to wonder how to make use of it to transmit messages, turning the layer into a kind of telephone.

There is reason to believe that this natural telephone has long been used by sperm-whales. These enormous creatures differ from other inhabitants of the ocean not only in their size but also in their habit of frequenting the farthest corners of the World Ocean. Besides that, only whales can dive to a depth of one kilometre though they spend practically all their time on the surface of the ocean. Thus, knowing about the underwater sound-conducting layer, we can finally provide a reasonable explanation of another mystery: how whales manage to find each other

in the vast World Ocean. Whales do not just happen to meet each other in the ocean expanses, but seem to retain family ties over a long period of time, and also maintain friendships which would be difficult to keep up were it not for their "telephone" or "mail" system. Unfortunately, this is still a hypothesis. Even if we assume that the sea rovers talk with each other once in a while, we still don't know how they arrange to "step into the telephone booth" at the same time — after all this involves diving to a depth of nearly one kilometre.

Even the ancient Greeks knew that whales, as distinct from ordinary fish, have a real voice. Later this was completely forgotten, but today the voices of whales and, if we can call it, their language have been closely studied. Whales can produce ultrasonic squeaks which serve for echo-soundings as in the case of bats. But besides communicating with each other, whales use sounds within the audible range. Recordings made with the help of hydrophones feature quite coherent "statements", sounds resembling mewing, barking, mooing and even a grating sound. The variety of sounds in whale "conversation" prompts many researchers to conclude that whales do have a developed language

Slowly But Surely

In considering how sound travels in matter we have noticed how easily this occurs, and the wonderful feats it performs along the way. Though, the brilliant picture faded when we turned to infrasonic waves which probably cause more harm than good. But the sounds we hear do not always serve people as a humble slave. Since people have started to make machines they have been concerned with productivity, speed, power, and sometimes convenience in work. Hardly anyone thought about the noise they made. This was only natural. People of the past had plenty of quiet, and we don't usually appreciate something we have in abundance.

That abundance, however, quickly began to disappear. The inhabitants of medieval towns were already beginning to suffer: waggon wheels rumbled, street vendors shouted and craftsmen's hammers were heard all day in the narrow streets. And at the beginning of this century life in the big city became a veritable hell in terms of noise: streetcars rattled, motorcycles sputtered, automobile horns honked, factories rumbled, and later

You can see the bell but you can't hear it: the best sound insulator is under the glass — vacuum

airplanes roared, driving any unaccustomed person mad.

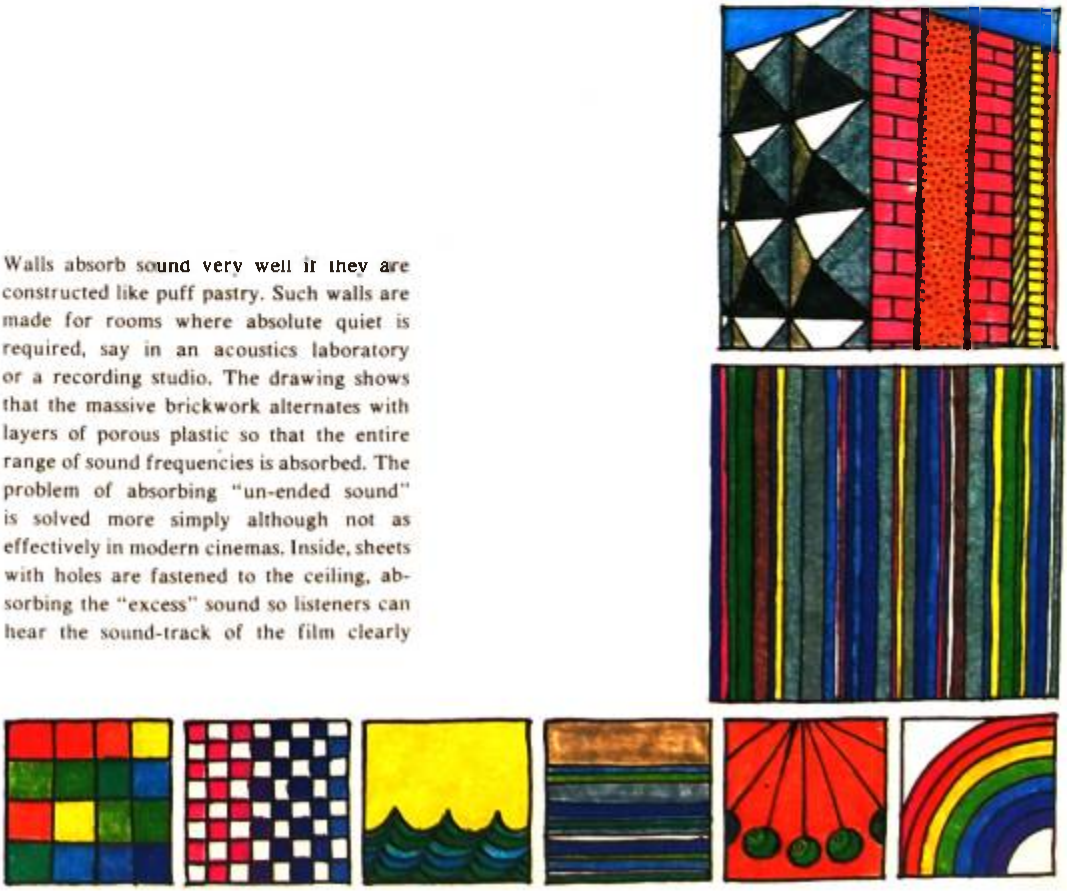
When the situation became critical doctors entered the scene, and their research showed that sound was not simply bothersome and tiring. It could seriously undermine health, and not only one's hearing but his entire nervous system. A new term appeared: noise pollution. At first ordinary administrative measures were adopted throughout the world: plane flights were banned over cities and high-speed railways were transferred outside city limits.

This helped, but only for a while. More serious measures were necessary. An appeal was made to the engineers responsible for the development of roaring and rumbling machines. The engineers must quiet down their excessively noisy "offspring". As soon as people declared war against noise, two trends emerged in science and technology: one sought ways of avoiding any noise in principle, while another tried to reduce noise which was impossible to do away with. First of all, attempts were made to reduce vibrations in machines and improve ball-bearings and mufflers so they would not make noise. Machines were no longer permitted to screech, rumble or rattle. Incidentally those who were interested in productivity did not stand to lose either: the quieter a machine works the less wear and tear and the more reliable it is. It proved most

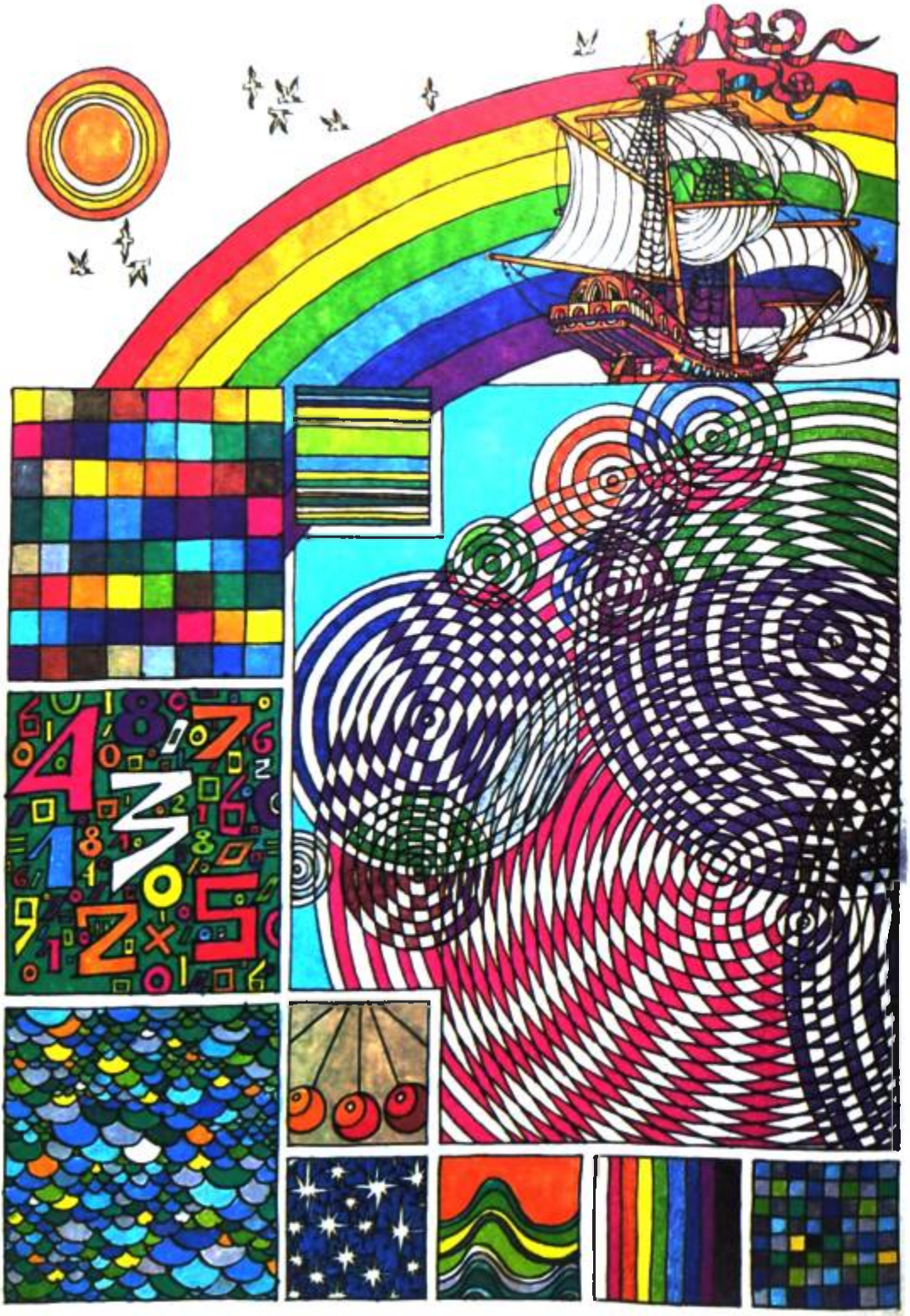
difficult to reduce noise that has already emerged: sound penetrates almost any obstacle, even the thickest walls. Despite all the special sound absorbing padding and sound reflecting obstacles, there is little success in this field. The general rule is: if you want quiet, don't make any noise. This rule of engineering courtesy applies to you as well. Don't stamp on the floor, particularly in the evening. Even the thickest floor will not protect your neighbour downstairs from the noise. If you want to shout, don't do it at the top of your lungs: you're not the only one who hears the shout.

Does this mean there are no effective obstacles to stop sound? No,

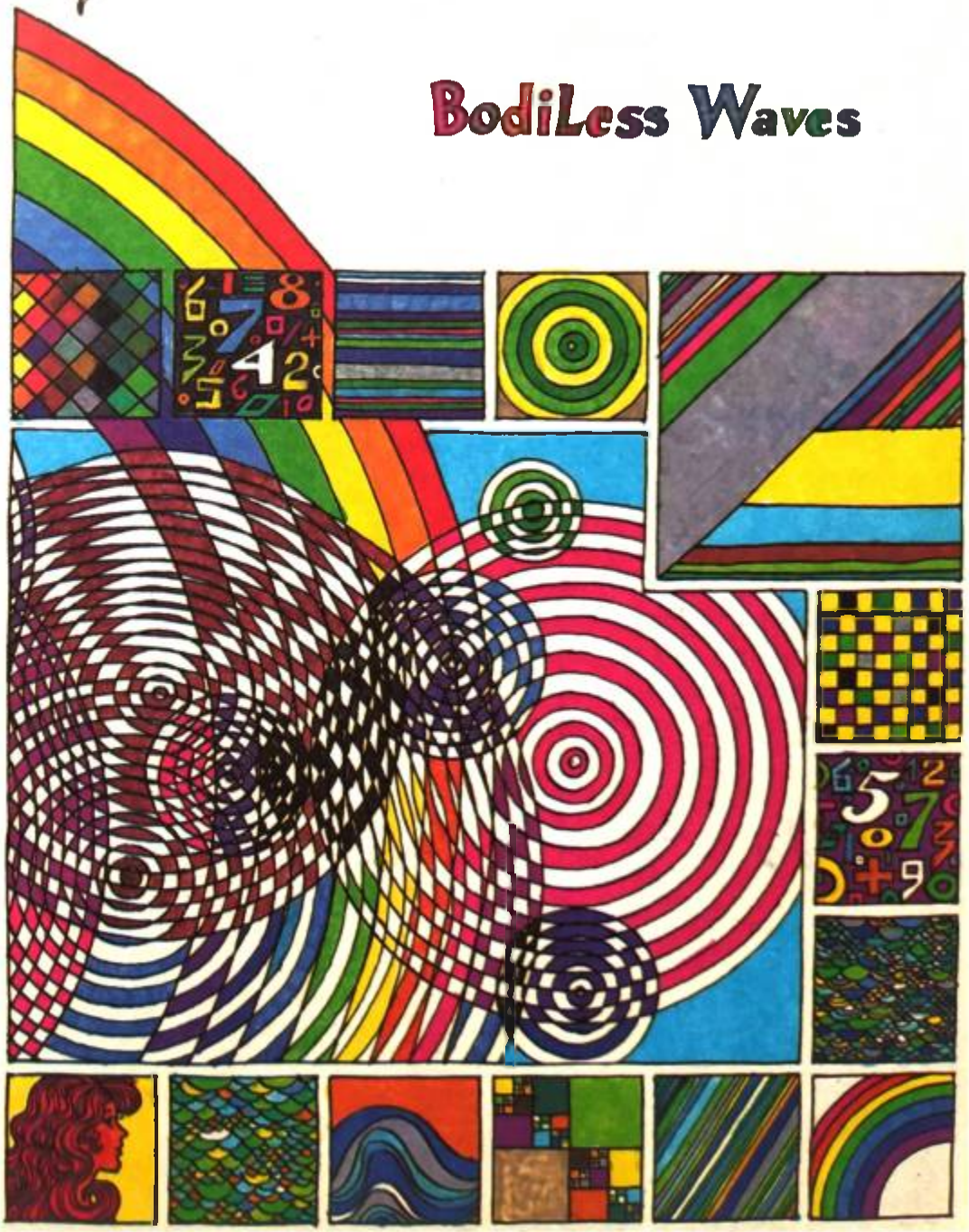
it doesn't. Sound can be stopped by a vacuum, absolute emptiness. If there are no particles to transmit the elastic waves, sound won't spread either. This was confirmed a long time ago by the following experiment. A bell was put under a glass cover and made to ring by means of a special device. The sound naturally went through the glass and reached the listeners' ears. But when the air was pumped out from under the glass, the bell lost its voice. It could be seen how the bell swung but there wasn't a sound. On Earth sound waves exist because they remain within the atmosphere. But outer space is indeed a kingdom of silence. The emptiness of space is an obstacle which cannot be overcome by any waves, except...

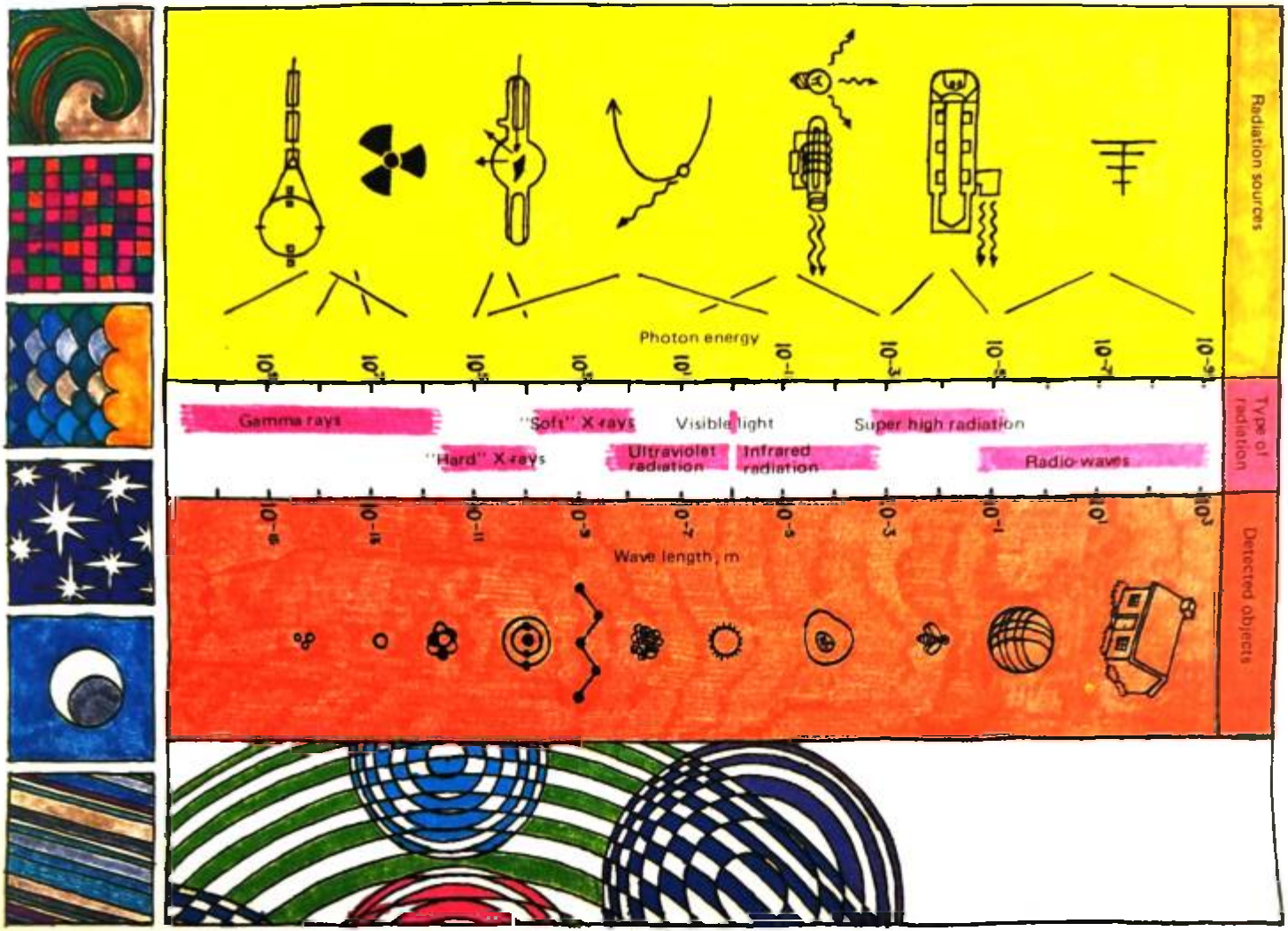


Walls absorb sound very well if they are constructed like puff pastry. Such walls are made for rooms where absolute quiet is required, say in an acoustics laboratory or a recording studio. The drawing shows that the massive brickwork alternates with layers of porous plastic so that the entire range of sound frequencies is absorbed. The problem of absorbing "un-ended sound" is solved more simply although not as effectively in modern cinemas. Inside, sheets with holes are fastened to the ceiling, absorbing the "excess" sound so listeners can hear the sound-track of the film clearly



BodiLess Waves




Radiation sources
Photon energy
Type of radiation
Gamma rays
"Soft" X-rays
Visible light
Super high radiation
"Hard" X-rays
Ultraviolet radiation
Infrared radiation
Radio-waves
Wave length, m
Detected objects

The Story of Imaginary Ether

Emptiness is an obstacle for all waves except electromagnetic waves! These waves are unusual, and are difficult to explain, so pay close attention.

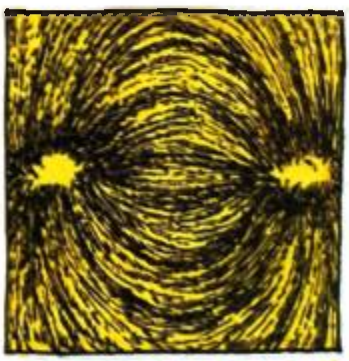
You have known about most electromagnetic waves since you were very small: these are ordinary light waves which come from the Sun and the farthest stars travelling millions of kilometres through the emptiness of outer space. If sound travels about three hundred and forty metres a second in air and about one and a half kilometres through water, light travels three hundred thousand kilometres a second through emptiness! It is almost impossible to imagine such a tremendous speed, and at the beginning of this century scientists realised that it was the greatest speed in the world, a record that can't be beaten. For a long time scientists were troubled by the question of how light waves travel through absolute space. In order to solve the riddle, physicists did the following: they decided to imagine that all space was filled with a substance called "ether". Of course the ether sold in drugstores has nothing in common with this invented ether. They assumed that ether had no weight, colour, or smell and had no noticeable qualities in general. Yet it possessed a certain elasticity thanks to which the waves, now called electromagnetic waves, spread through it. The explanation was convenient. It helped physicists for a while, introducing some system into their knowledge. But is it reasonable to explain one unknown phenomenon by another which you understand no better and which, moreover, might not even exist?

It would be appropriate at this point to recall the teachings of the English philosopher and monk William of Ockham. Although he lived in the 14th century and did not engage in scientific activities in our sense of the word, William of Ockham left some general rules of correct thinking useful to anyone who wants to avoid making mistakes. One of his rules reads: don't invent unnecessary entities. In other words, in attempting to understand something or explain complicated problems don't create new things which we can do without or which are themselves unknown. That rule is called Ockham's Razor, cutting away at any incidental or doubtful inventions.

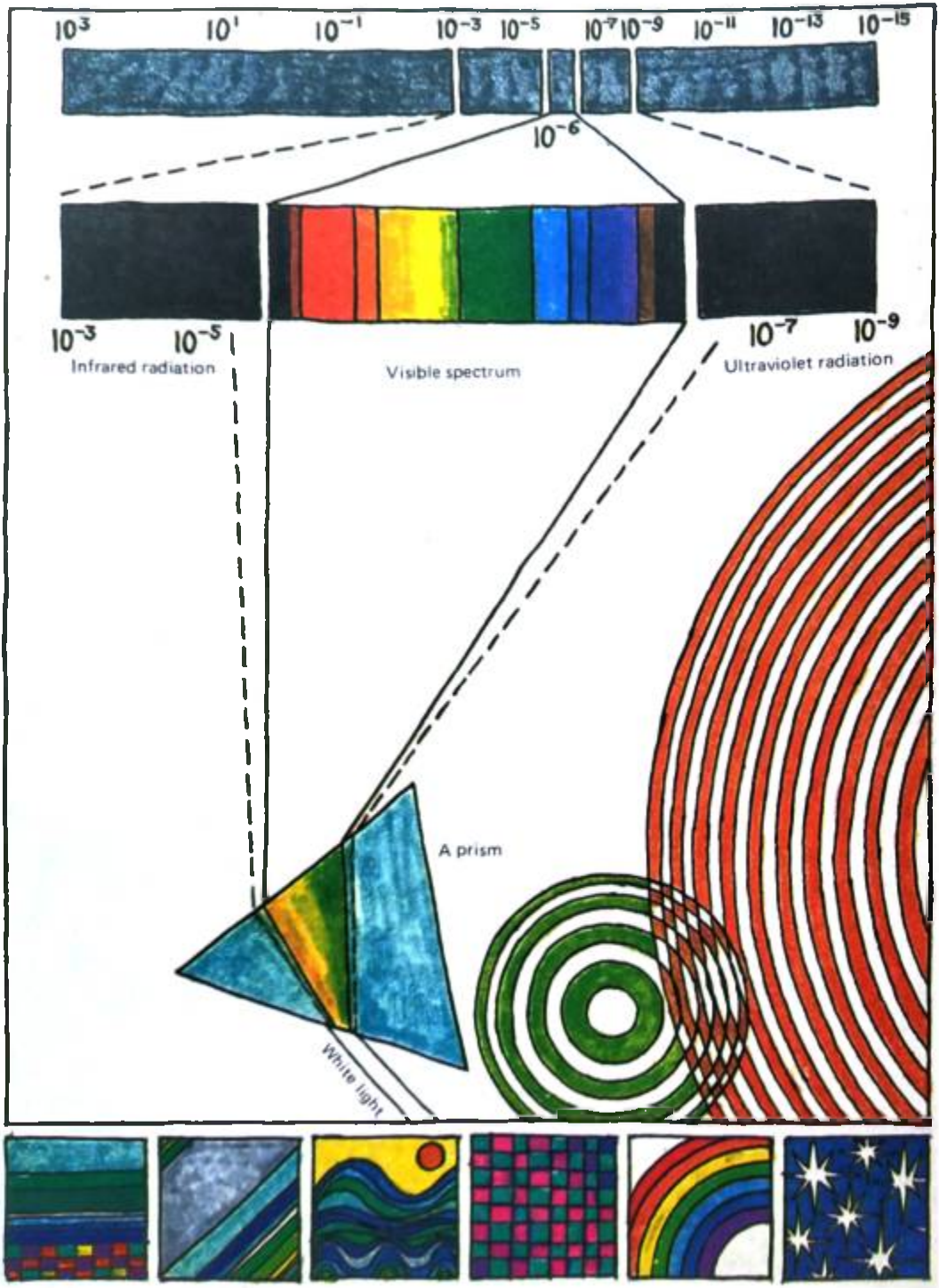
Ockham's Razor seemed specially made to reject the reasoning of 19th-century scientists concerning ether. But ether was abandoned only when it had led scientists to a dead end and no tricks could help explain certain natural phenomena. Then scientists remembered the magnetic and the electric fields.

Everyone knows, of course, that something exists around the magnet which causes the needle of the compass to turn, nails to stick to its poles and other similar miracles to occur. That something is the magnetic field. Like ether it has no taste, colour or smell, yet it exists as an ordinary compass shows. The electric field existing around electrified objects is somewhat similar. A vacuum is no obstacle for these fields. The magnet attracts nails in outer space, too, and the electrified comb picks up little pieces of paper in a vacuum. And if the magnetic or electric field is abruptly changed in some particular spot, electromagnetic waves will radiate in all directions, and the behaviour of these waves will be reflected only in vibrations in the field's force. Scientists attempted to consider the

existence of electromagnetic waves from this viewpoint, and right away many confused and isolated observations fell into place. One system emerged in which the iron magnet, lightning and ray of sunlight are close relatives. These are very interesting waves. To begin with, neither the magnetic, nor the electric wave can exist separately. During wave motion the electric field continuously turns into a magnetic field and vice versa. The height of these waves does not exist to all intents and purposes: the force or potential of the field is not measured in centimetres. It is more convenient to use volts to measure their amplitude. Electromagnetic waves conform to the same laws which govern the movement of sea waves and sound waves, so it is advisable to take another look at the beginning of the book. Only light waves are very small: their length is about a million times smaller than a millimetre, so it is simply impossible to see them. But if we think about it, the very idea of seeing a light wave is absurd. To see is to feel the light waves falling on our eyes. How is it possible, indeed, to see a light wave by means of the wave itself?



You can't see electromagnetic fields with the naked eye, but you can gain an idea of their shape from the way they influence other objects. The filings on the drawing indicate the lines of force between the magnetic poles


10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11} 10^{-13} 10^{-15}
10^{-6}
10^{-3} 10^{-5}
Infrared radiation
Visible spectrum
10^{-7} 10^{-9}
Ultraviolet radiation
A prism
White light

The Rainbow

Do we have to mention the importance of light for people? Anyone can think of dozens of examples to show how joyless life would be without light. It is better to look at the unusual properties of light which one doesn't encounter every day. Take the rainbow for instance: this colourful show is staged in the sky by ordinary sunlight. Just as swells it consists

Occasionally, nature constructs a mock spectroscope out of anything available, for instance, a mist after rain. Tiny drops of the haze after a thunderstorm act like millions of prisms for the sunlight. Then the ordinary white light appears to us in regularly arranged colours: red, orange, yellow, green, blue and violet, always in this order

of many waves of different lengths, only in sunlight each wave length conforms to a certain colour. Rays of different colours behave almost indentically, but it is possible to separate them nonetheless. A device which does this is called a spectrograph: it obtains and photographs the spectrum, or divides the complex light wave into the separate waves that make it up.

Different sources yield light of different shades. Sunlight is almost white, the light of a desk lamp is yellow, burning gas is blue, coals in a bonfire are red, and the stars in the sky may be all the colours of the rainbow. The colour emitted by any substance when it burns or is subjected to intense heat has a lot to say about its chemical composition. If the light is broken up in a spectrograph and we determine the waves it consists of, it is possible to indicate all the substances being burned. That is what chemists do, for example: by means of spectral analysis they can detect admixtures in a substance, which could not be discovered otherwise. The spectrograph is invaluable to astronomers: they can learn what stars are made of only from the spectrum of the light coming from them. One chemical element on the Sun was discovered for the first time in this way. The element was called helium which is derived from the Greek word **helios** meaning Sun. Just by looking at the Sun, people discovered a gas which had never been seen on Earth (only many years later was pure helium obtained in a laboratory). But the spectrum serves to identify not only light waves but also any other waves or vibrations — sound, sea waves and the swinging of the pendulum.

It is not easy to focus light: anyone who has used a flashlight or done poker-work with a magnifying glass knows this. The beam of a flashlight narrows only to a certain extent, and the spot of light made by a magnifying glass is not as small as we would like it. There are many reasons for this, and some of them cannot be overcome.

But if we take a crystal, a ruby, for example, and "fill" it with light energy by means of a flash (similar to the one used by photographers),

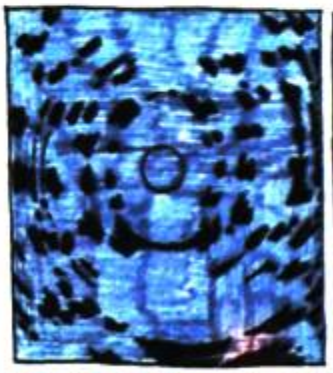
under certain conditions the crystal will suddenly begin to emit its own light — a very thin, remarkable, red ray. The "flashlight" producing this light has been called a laser. Today many lasers of the most varied designs have been made using different crystals, gases and liquids which emit the wonderful ray, and the laser beam has found many applications. It is much better to do poker-work with a laser than with a magnifying glass. The laser, moreover, can burn a hole through any material, even a diamond. It makes a tiny hole one thousandth of a millimetre wide in the hardest steel. Enormous energy can be stored in it: even passing through transparent glass the laser beam leaves a trace. In many fields the laser has usurped the position of our old friend, ultrasound. The laser is also an essential tool in medicine. In extremely delicate operations — on the eye, for example — it replaces the surgeon's scalpel. The laser is sharp and sterile, and it can disinfect the wound itself. For a long time scientists and engineers had dreamed of a beam that did not dissipate over long distances. The dream came true with the laser beam. If an ordinary flashlight can be used to transmit signals over long distances, the laser works even better. If the laser beam is furnished with information, the message can even be transmitted to another planet.

Another remarkable quality was discovered in the laser. If ordinary sunlight is a confused mix of the most varied electromagnetic waves, waves in the laser beam have one and the same length. Since that is so, it is possible to count the waves that lie between the laser and some obstacle the beam has reached. Thus, in addition to everything else, we have obtained an excellent ruler whose length varies from several millimetres to many kilometres, while the scale remains the same — an error would be not more than the length of a light wave, much less than a thousandth of a millimetre. And there is still more. To explain all the laser can do would require a whole new book.

"Rigid" Light

Not all electromagnetic waves are visible to us. As in the case with sound waves, the human being is capable of perceiving only a small part of all electromagnetic vibrations. At first, let's find out what we have on the right of the spectrum, on the side with higher frequences. After violet light comes the zone of ultraviolet light. The waves of this band are similar in all respects to ordinary light, only we can't see them. But our skin perceives them very well, and tans because of that light. A suntan is not only attractive, it is very important for one's health. If a person does not get enough sunlight with sufficient ultraviolet rays, he needs ultraviolet light treatments, just like he needs to take vitamins if his body is not receiving all that it requires. There are special lamps for the purpose: they emit less ordinary light and more ultraviolet. Incidentally, that light also kills

This familiar picture was drawn by an X-ray. The X-ray picture is a negative. The tone of the image is lighter in the places where less rays have got, as it is due to the denser tissue. In this way the X-ray doctors can examine a person's bones, searching for fractures, and they can also notice various inflammations and tumours in soft tissue, because the rays pass through them in a slightly different manner



It is impossible to examine molecules, the minute yet highly complicated structures all substances consist of, in ordinary light by eye, even by means of the best microscopes. The waves of visible light are too long to provide an image of a molecule when they are reflected. X-rays are quite different. The drawing shows an X-ray photograph of a complex biological molecule of deoxyribonucleic acid. Strictly speaking, however, we can only earn how short and hard X-rays are dispersed by its "skeleton", but even this tells us a great deal about its inner structure

harmful microbes. The analogy with vitamins is not accidental here. Indeed, some vitamins we need to live are produced in the skin under the impact of ultraviolet light. But as with vitamins, one should be careful: too much sunlight can be harmful, too.

Probably everyone knows about X-rays which doctors use to look inside our bodies. These are situated higher than ultraviolet light on the scale. These rays pass easily through our body: only bones prove to be a serious obstacle for them. That is why a person seems to be semi-transparent on X-ray photographs. The X-ray light is invisible, of course, and the doctor examines the patient's internal organs on a special screen: the screen radiates ordinary visible light in places where the X-rays fall.

The higher the frequency of electromagnetic waves, the more energy they carry and the "harder" its radiation. X-rays are hard enough to pass through the human body, while gamma rays can be stopped only by many metres of earth or heavy steel armour. These waves are dangerous: if they pass through the body they may irreparably damage the molecules in our body. It is particularly dangerous if the hard rays reach the complicated molecular chains containing information on heredity. The slightest change even in one link of the chain, and a future child may develop differently from his parents. But strong radiation continuously falls on Earth from outer space! How, then, are all living things on the planet protected from destruction and inevitable degeneration? What shields us from the lethal rays?

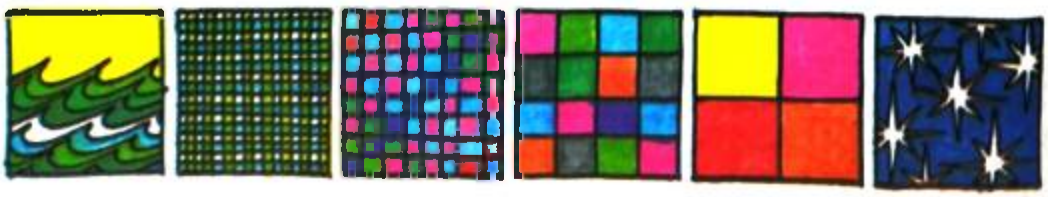
That shield is the atmosphere enveloping the whole planet like a warm, impenetrable coat. There is a hypothesis that millions of years ago either the atmosphere didn't work as well or the radiation from space was stronger. Life, which was just appearing, was not wiped out, instead the immense variety of plants and animals we have today evolved due to continuously changing heredity. Selection experts also use radiation to develop new plant species. If plants or seeds are exposed to radiation, numerous new forms will appear in the next generation, and the ones that possess the required properties can be selected.

Heat Rays

Let's look at the left side of the scale of electromagnetic waves. Just beyond the red comes the invisible infrared. The waves of the infrared band are responsible for transmitting heat. If the Sun didn't emit infrared rays, it would be much colder on Earth since half the Sun's emissions constitute heat rays.

Some of the properties of heat waves may be deduced without any experiments or observations. All we have to do is jog our memory. Remember how hikers around a camp-fire warm themselves in cold weather: they change their position all the time, turning one side to the fire, and then the other. Why, when you warm your hands at the fire, does your back grow cold, and when you turn your right side to the fire, the left side freeze? Because near the fire we are warmed by infrared radiation more than by the warm air, and like visible light, it travels in straight lines and heats only the objects it falls upon. If it becomes too hot at the fire, it is always possible to hide from the radiation, say behind your neighbour's back. Later the fire goes out. Darkness falls, and instead of the brilliant fire there is only a pile of glowing coals, but even they emit invisible rays of warmth.

The drawing shows a photograph made in infrared rays, and the different-coloured strips and spots enable us to determine the temperature of a person's skin with great precision. It is possible to use an ordinary camera to make photographs in infrared light, but for that we need a special film sensitive to infrared rays. The camera must be metal and not plastic, because plastic is transparent to infrared rays



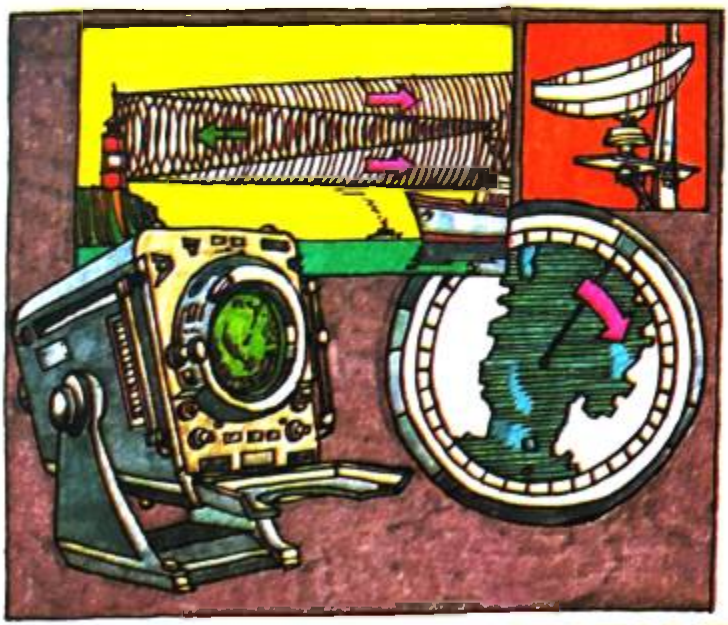
We can learn another property of thermal radiation or heat waves by means of a simple experiment. Put a few pieces of coloured fabric on the snow on a sunny winter day. What we see in the evening will enable us to draw very important practical conclusions. Warmed by the sunlight, the bits of fabric melt the snow under them and sink in small hollows — the darker the fabric the deeper it settles into the snow. The conclusion is obvious: the darker an object's surface, the better it absorbs heat waves. Let us add that the same thing holds for radiation: the lighter in colour the surface, the less infrared waves it emits. Knowing this law we can make some suggestions: first, winter shoes should be white so your feet are not cold; second, for stoves to be warmer in rural homes, they should be black. However, these suggestions are not mandatory: the actual effect of these changes is not great enough to warrant breaking established traditions.

An ordinary reflector heater is an excellent infrared projector. But why does it need a polished reflector like the one in a headlight? The weak red light it emits would not illuminate anything anyway. But a reflector heater works differently from a stove or heating battery. It is not very warm at the reflector heater itself, but the objects the reflector is aimed at are very warm — it sends infrared rays, and therefore nearly all its heat to these objects. If infrared light consists of heat-bearing rays, it is to be expected that invisible infrared rays are given off by all warm objects, at least slightly. And they are. In the daytime, everything surrounding us, including ourselves, bathe in sunlight, in the Sun's infrared and ordinary, visible rays. But at night, when it is dark, the warm human body can be a powerful "lamp" emitting invisible infrared light.

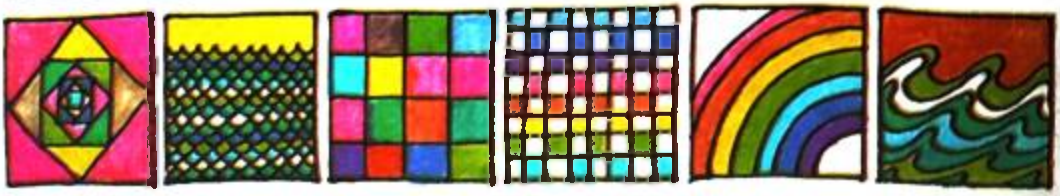
There are special night vision devices in which infrared light is transformed into a picture our eyes can see. Using a device resembling field glasses or a telescope, it is possible to see at night just as clearly as in the daytime, although the picture on the screen differs greatly from what we see in normal sunlight. The warmest objects stand out as white spots, so the asphalt road heated by the Sun in the daytime looks like a silver river flowing between nearly black grass.

Invisible Work

The bands of radio waves are the lowest on the scale. These waves occupy a very modest place in Nature and rarely manifest themselves. But people are very fond of them because of the work they do. Since they were discovered, they have come to mean nearly as much for people as sunlight. It is relatively easy to work with these waves. It is no problem to make a device to emit them, while any schoolchild in the higher forms can make an instrument to receive them — a simple radio set.



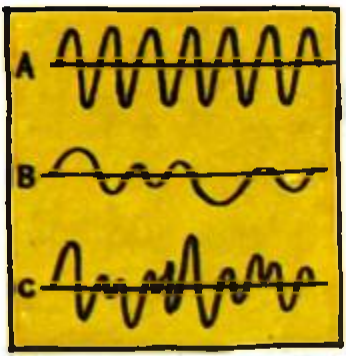
A radar



The Russian engineer Alexander Popov demonstrated his wireless set on May 7, 1895. As he put it, the set made up for the electromagnetic sense people lacked. In 1899 Popov's wireless was successfully used to rescue a ship in distress, and in 1900 a regular radio line was put into operation. Very soon radio waves replaced sound in many fields. Thus, radar, operating according to the same principle as night vision devices in bats but using radio waves instead of sound is now installed on all vessels and airplanes, enabling the captain or pilot to see through fog and darkness. Sound still serves us in the sea depths since radio waves do not spread well in water.

In order to transmit sound or pictures over distance, the radio station emits very powerful radio waves, and these waves are very complex since the sounds of the radio broadcast or pictures of TV are coded in them.

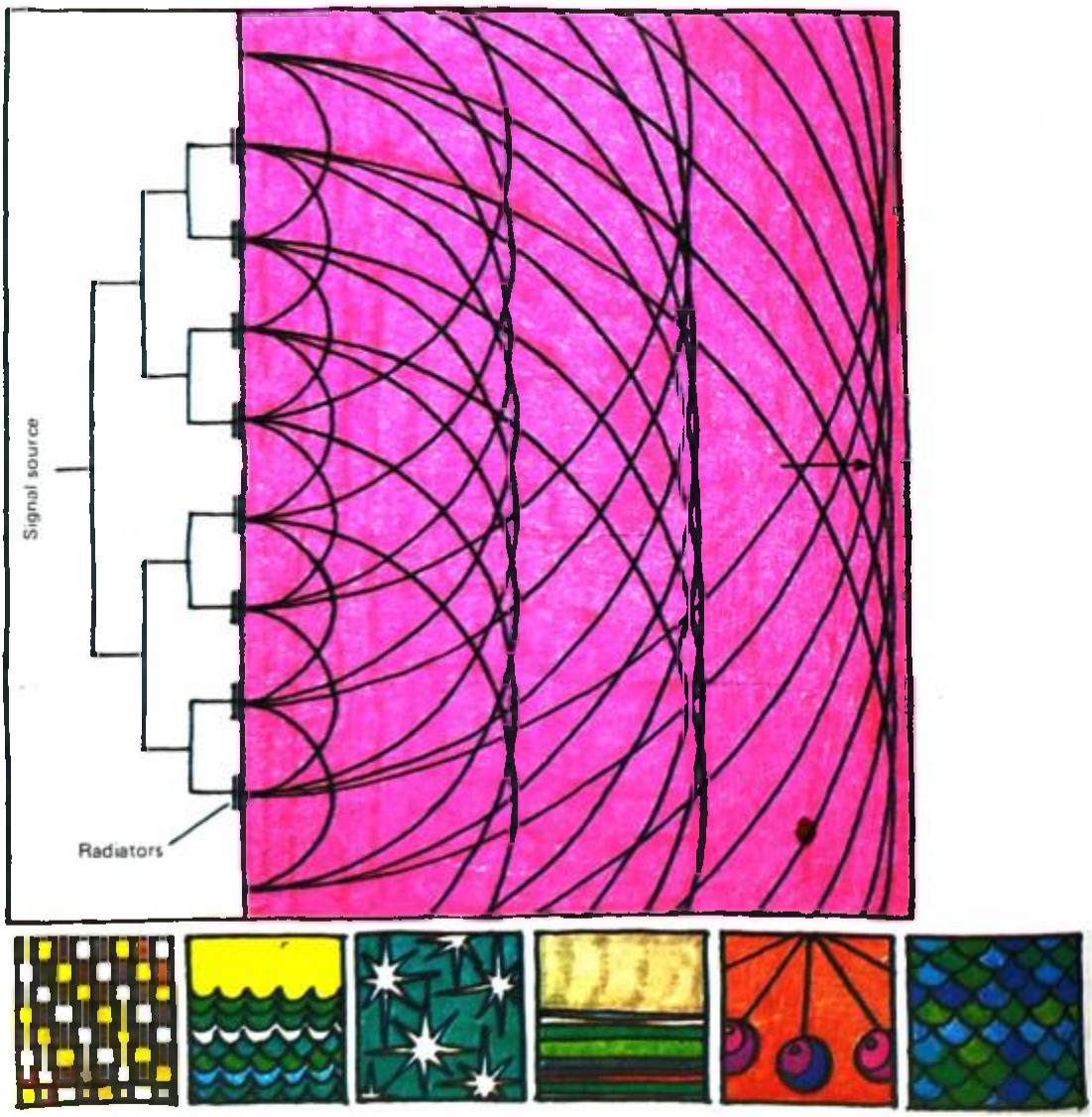
The reception devices (TV or radio sets) receive these waves and decipher the broadcasts they were furnished with at the radio or television station. This apparently complicated method of transmitting information



An ordinary electromagnetic wave carries no message. **A.** Now the transmitter is already working but the announcer remains silent and the radio-set remains silent. **B.** The announcer has started to speak, the drawing shows the change in the signal of sonar frequency coming from the radio studio. **C.** The radio wave begins to change in time with the announcer's voice. It is possible to understand what the announcer said only by means of various devices present in the simplest radio-set

has proved to be so convenient that today thousands of radio stations throughout the world broadcast so many programs that they hardly fit in the available radio wave bands.

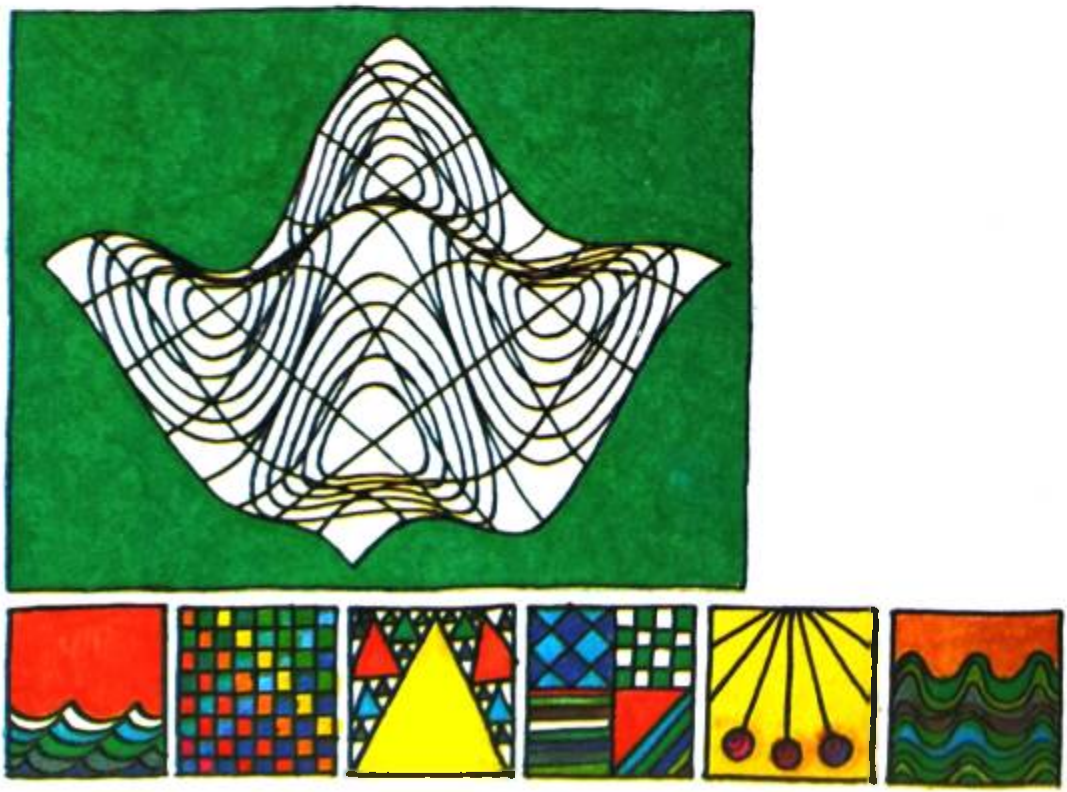
What about radio waves? Did they exist before radio transmitters



appeared? Of course they did. Only no one could "hear" them. Even today, if we turn the tuning dial of the radio set, we hear a lot of static — the sound of wild, untamed radio waves. Usually they behave, but occasionally, several times a year, these waves grow bold, and magnetic storms occur above the Earth. These are difficult times for ship and airplane radio operators: the static prevents any communications.

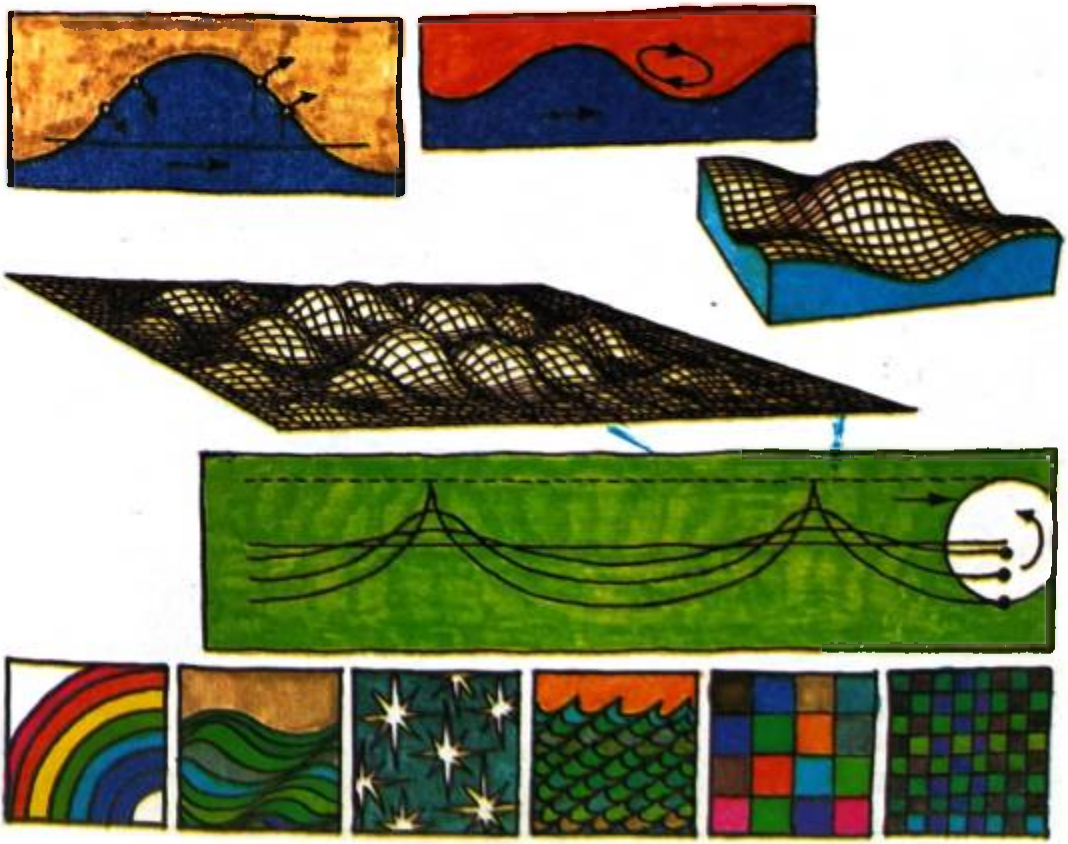
What Are Waves?

We have learned about some of the waves around us, travelling along the same road as people before us. First we considered the waves running along the surface of the water — everyone has seen them and the movement of these waves has been observed for at least two thousand years. In the last few centuries, however, many mysteries of this ordinary yet complex phenomenon have been solved. Then we talked about sound. People learned that sound was also a wave only about two or three hundred



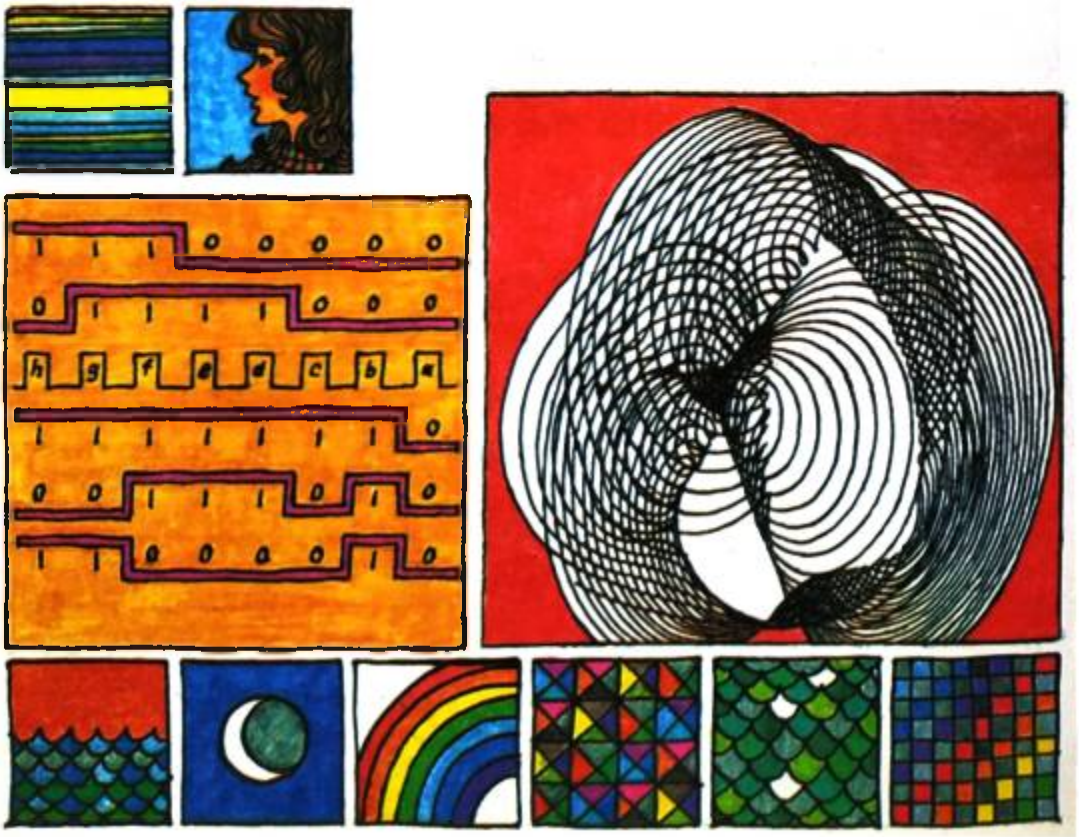
years ago. But by the turn of the 20th century the laws of sound oscillations were included in textbooks as several of the fundamental truths of physics — on a par with the laws of the movement of sea waves. This knowledge has been applied in our rapidly developing technology. An overall understanding of the laws governing electromagnetic waves was gained only recently — a hundred years ago — and the history of modern science describes the unceasing efforts of researchers to solve the mysteries of these waves.

Sea waves, sound waves and electromagnetic waves are three different elements. Why, in all three instances, do we call them waves? Let us recall the discussion on the pendulum and the musical string. If a phenome-



non submits to the laws of the pendulum, it involves oscillation and we can talk about a pendulum of an oscillating system. There is a similar formula to describe waves — the wave equation. All the waves we spoke of submit to it. Are there any other phenomena which may be called waves?

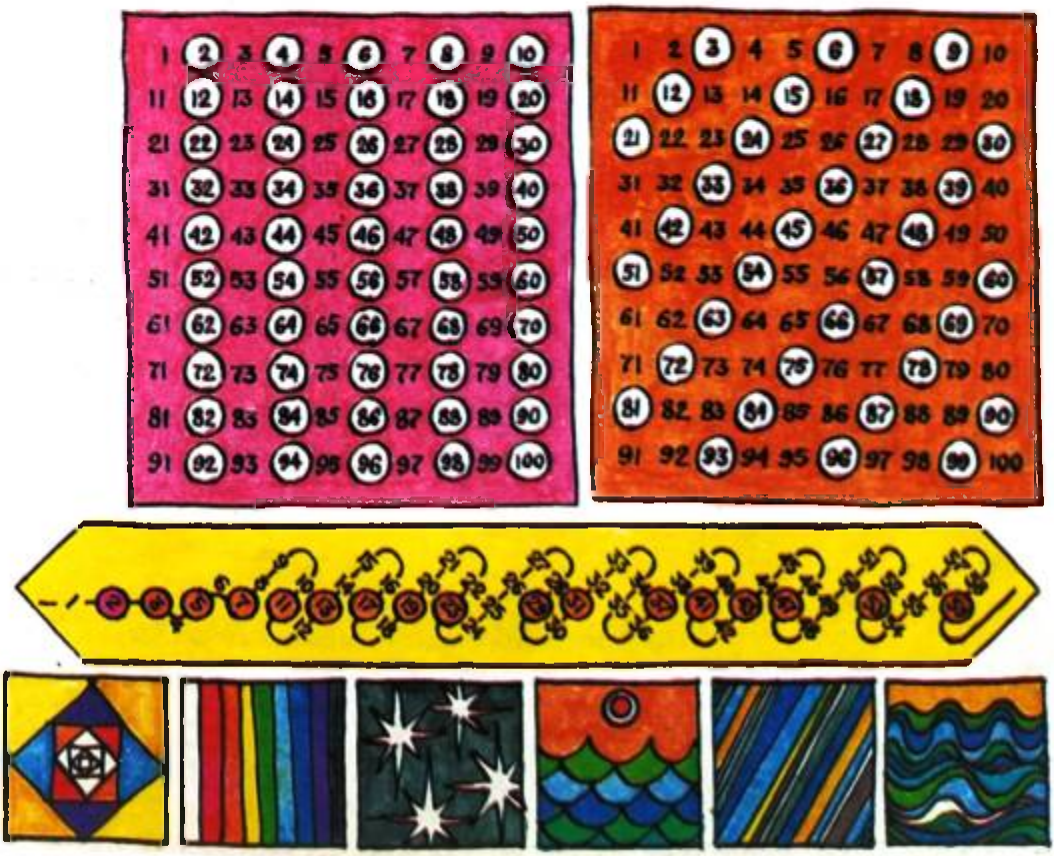
Let us take a look at the clouds floating over our heads. Among clouds of various shapes we often encounter wave-shaped ones. Why are they shaped like this? The clouds themselves are not waves but they reflect waves in the air. Indeed, the atmosphere is divided into layers just as the water in the ocean, and on the boundary between the layers, precisely where clouds are formed, atmospheric waves pass slowly, submit-



ting to the same laws as waves under the surface of the ocean.

Waves we still do not understand can also be found underfoot. The rock mass of the Earth on which roads are laid, rivers flow, and cities are built continuously heaves and changes shape. The strong basalt muscles of the continental plates flex under the thin skin of ground. As opposed to the rapidly moving and abrupt seismic waves, the waves of geological shifts are probably the slowest of all the waves we know on Earth. Such a wave may move a millimetre in a year, and a person would have to live several thousand years to see the rise or subsidence of a continental plate.

We can see some quite unusual waves if we approach phenomena



which seem to have nothing in common with waves according to the wave equation. Take, for example, the mysterious waves which govern the life of wild animals. If somewhere in the Siberian taiga the number of squirrels increases after a favourable year with plenty of food, waves of the squirrels will move into other areas and the squirrel will win new territories.

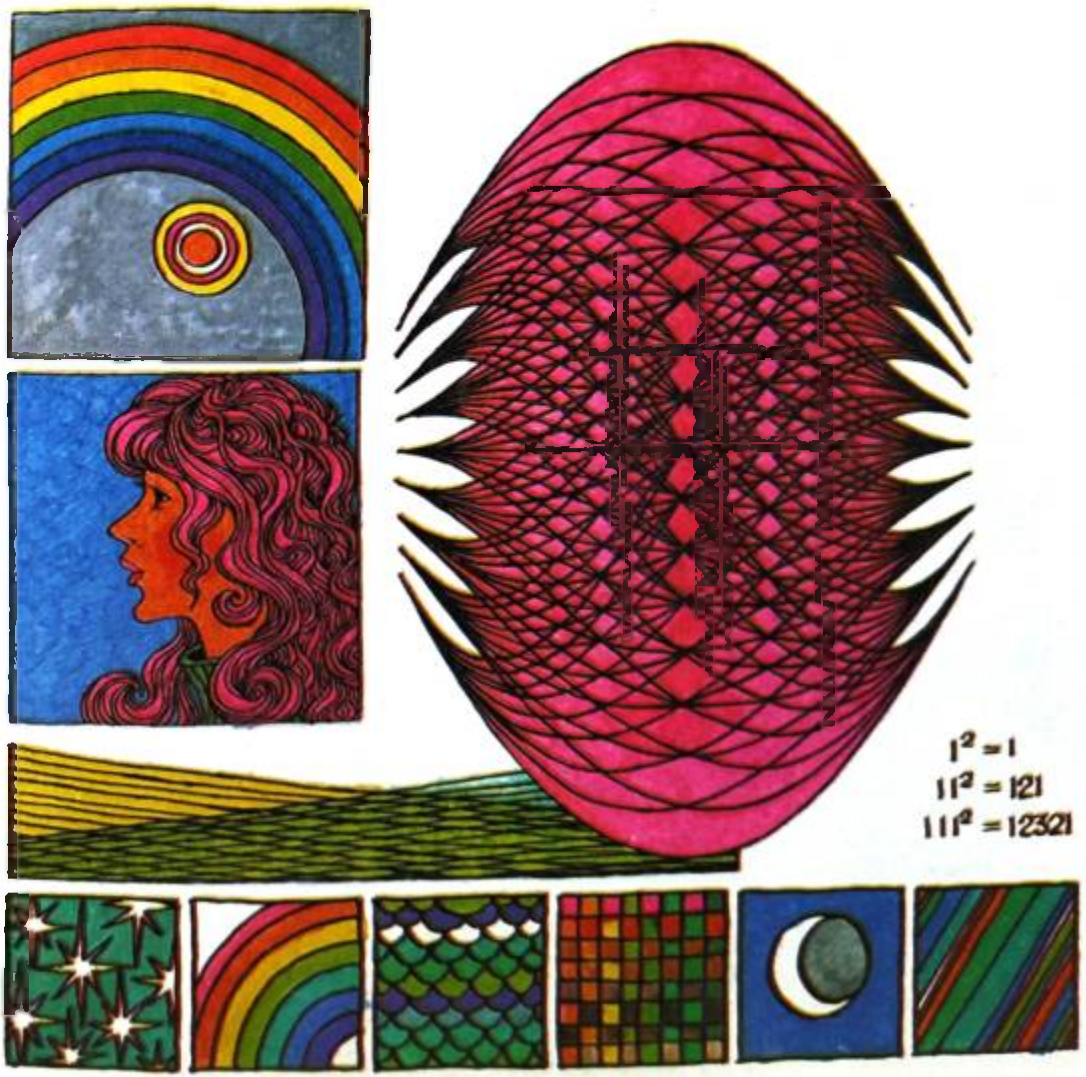
Prehistoric creatures came to shore from the ocean waves. Advancing stubbornly and retreating only for brief periods, in waves, they populated all the continents. And the waves of life continue to sweep through the Earth today.

Some of these waves would better be called "waves of death". These are waves of infectious diseases which ravaged the Earth. In the 1920s the Soviet scientist Alexander Chizhevsky discovered that epidemics of cholera or the plague obeyed the laws of wave movement, spreading out in rings from certain areas of South Asia throughout the globe. Moreover, the period of these terrible waves turned out to be precisely eleven years — coinciding with periods of solar activity. Apparently, the waves coming from outer space serve as some sort of signal for epidemics to begin on Earth. Today, medicine has set up reliable barriers against deadly epidemics, but waves of viruses still spread throughout the world.

If we look carefully, we will see waves not only in Nature but also in the artificial systems developed by man. Let us take the energy supply system of the entire Soviet Union. A wave of maximum energy use sweeps through the huge country every day, following the Sun's movement. It begins in the Far East early in the morning when people first turn on the light upon wakening, and offices and plants start to work. When that wave reaches the western frontier, there is a decline in the east and the power engineers prepare for the new wave to come the next day.

Conclusion

Wherever one looks, waves are living their inconspicuous lives and doing their invisible work. Even in you, yourself, all the capillaries are vibrating, blood is running through your arteries in waves, and electric waves are sweeping along nerves. As you read this page, waves are rushing from your eyes to your brain.



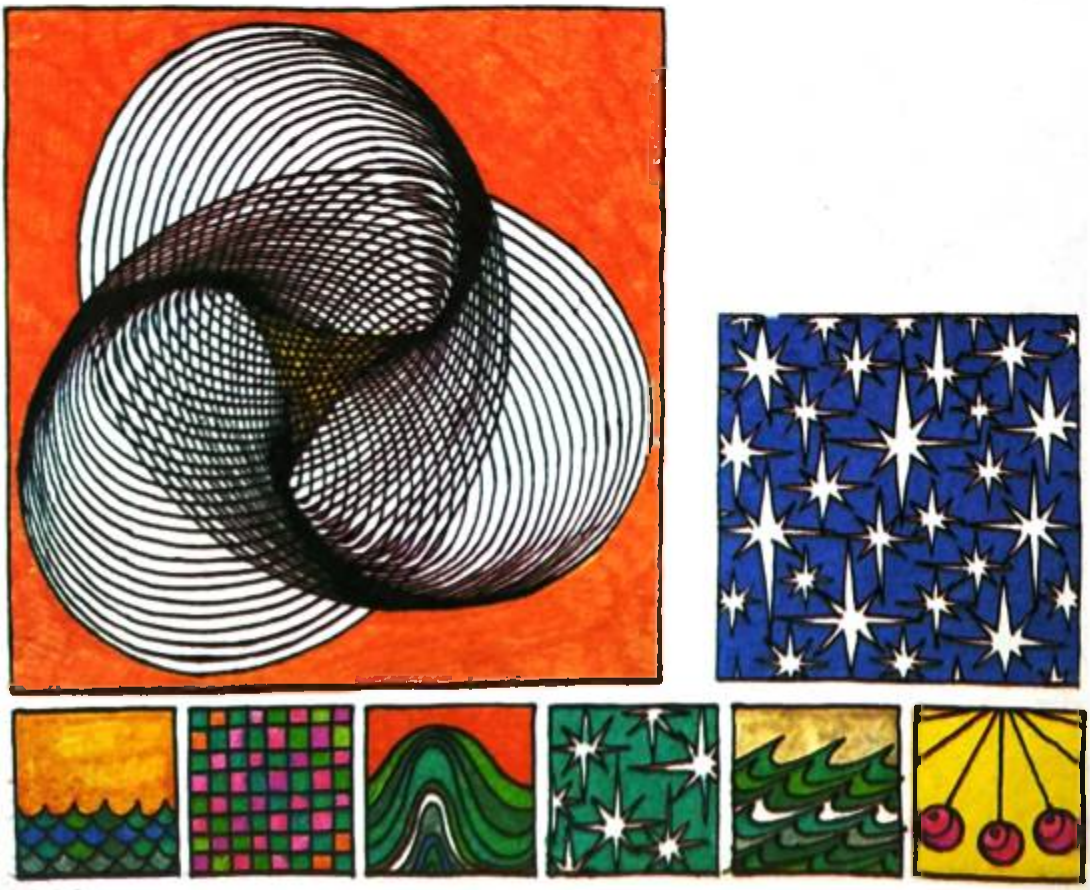
How do waves differ from other phenomena of Nature? By the patterns common to all waves! If something vibrates, pulsates or breathes in Nature — then there is a wave. If something moves into the distance without leaving a trace — that is also a wave. If you observe Nature more carefully, you will see many waves which have not been discussed here.

The series of gently rising hills on the Russian plains are waves slowly moving along the Earth's crust for millions of years.

The flickering of the flame in a dying camp-fire also gives off waves, complex waves of chemical reactions.

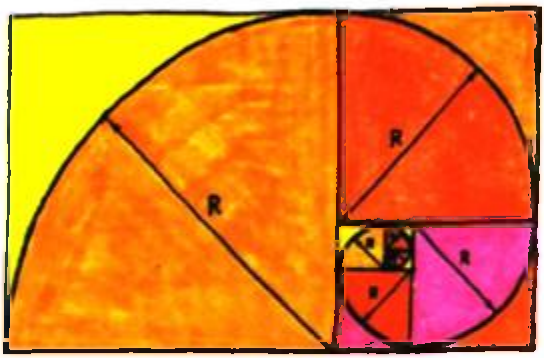
The traffic speeding from corner to corner is also a wave, governed by the law of wave motion as is a crowd of commuters.

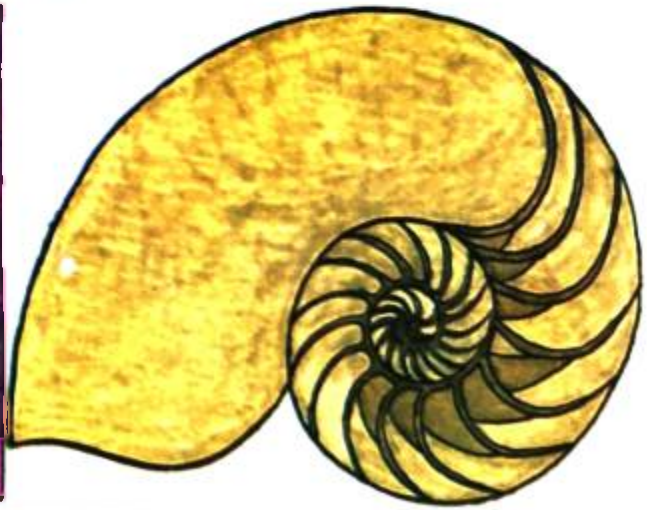
The steep spiral of a distant galaxy is also a wave, a compression wave of enormous masses of matter behaving according to laws still undiscovered. Modern science already believes that atoms, the building blocks making up



everything in Nature, are a complex intertwining of electromagnetic waves and others, even more mysterious.

The world appears to be a kingdom where various vibrations, or waves, rule. And the fact that not all of them have been discovered is, perhaps, the most remarkable thing about the world. It is impossible to discover all of them, because each new discovery gives rise to new questions. Such is the path to knowledge, knowledge of the surrounding world. The most wonderful part of Nature is what is still unknown. So seek the unknown and ask more questions: a good question is already half the answer.





REQUEST TO READERS

Raduga Publishers would be glad to have your opinion of this book, its translation and design and any suggestions you may have for future publications.

Please send all your comments to 17, Zubovsky Boulevard, Moscow, USSR.

Перевод сделан по книге:
А. Ракин. «Волны большие и маленькие».
М., Издательство «Детская литература», 1984 г.
Редактор русского текста М. Е. Шумская.

Для среднего школьного возраста

ИБ № 6061

Редактор русского текста М. Шумская. Контрольный редактор А. Буяновская. Художники Валерия и Александр Сафоновы. Художественный редактор А. Томчинская. Технический редактор Г. Немтинова. Сдано в набор 12.05.89. Подписано в печать 25.10.90. Формат 70x90/16. Бумага офсетная. Гарнитура Тип Таймс. Печать офсетная. Условн. печ. л. 8,19. Усл. кр.-отт. 33,34. Уч.-изд. л. 7,8. Тираж 18500 экз. Заказ № 2641. Цена 1 р. 20 к. Изд. № 5945. Издательство "Радуга" В/О Совэкспорткнига Государственного комитета СССР по печати. 119859, Москва, ГСП-3, Зубовский бульвар, 17. Предприятие малообъемной книги дважды ордена Трудового Красного Знамени Ленинградского производственного объединения "Типография имени Ивана Федорова" Государственного комитета СССР по печати. 192007, Ленинград, ул. Боровая, 51.